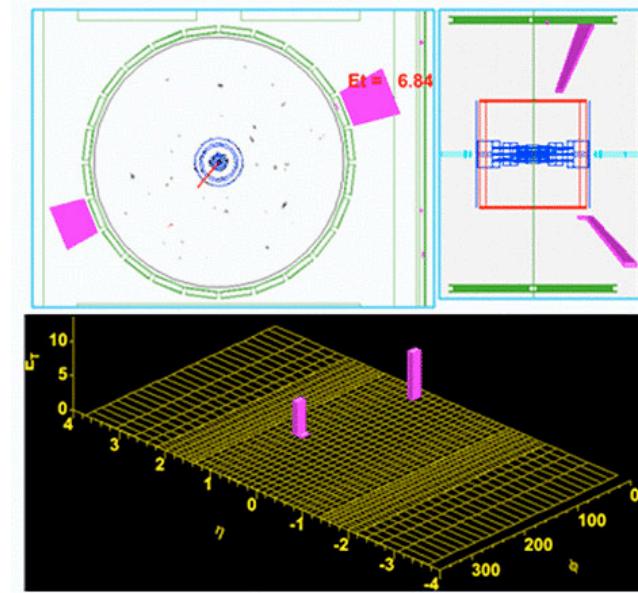
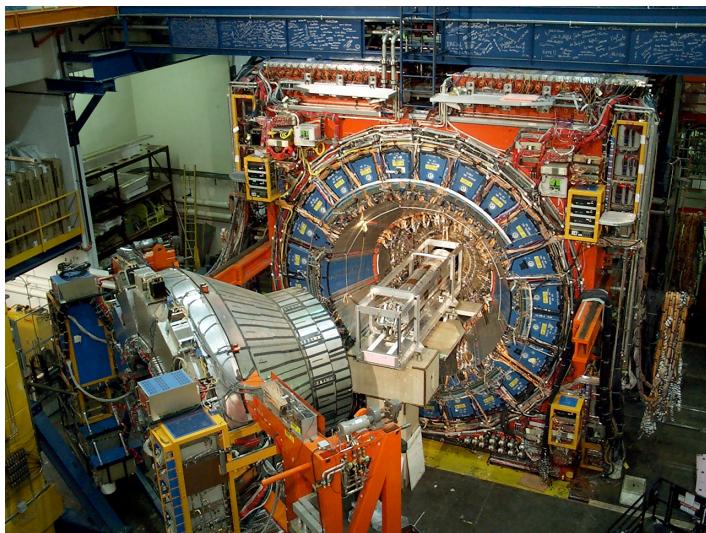


New Photons Results from CDF

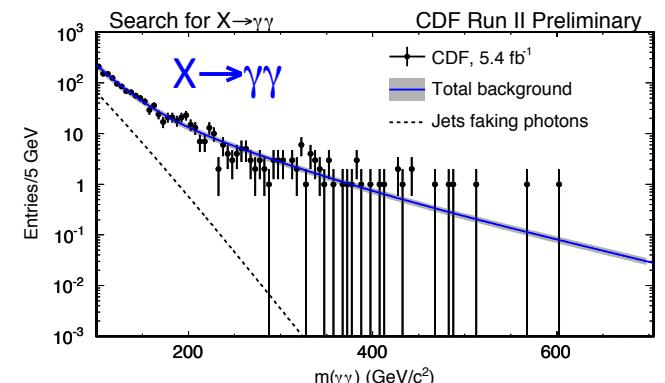
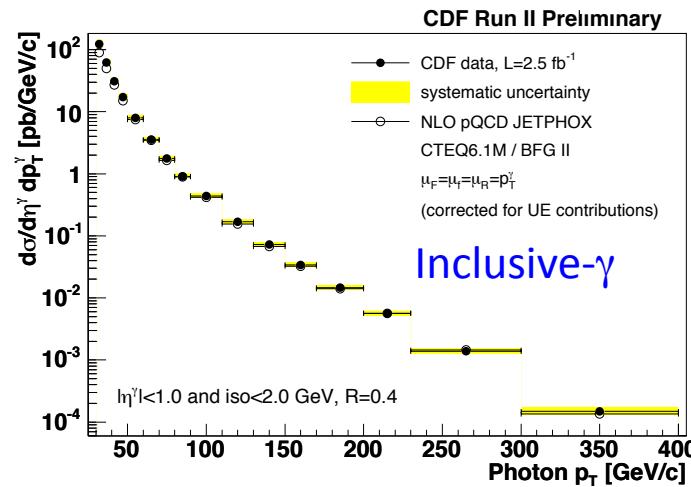
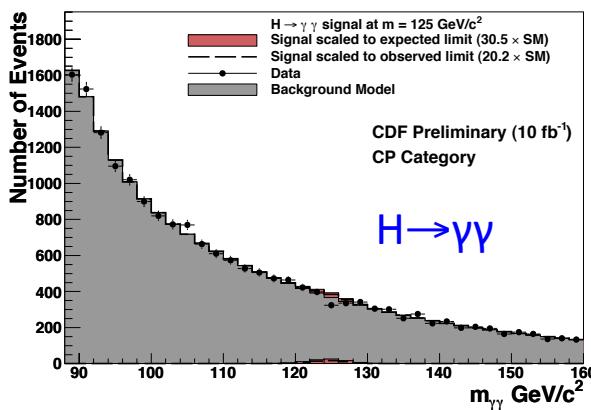
Tingjun Yang for the CDF collaboration
Fermilab

Joint Experimental-Theoretical Seminar
Fermilab, 2013/03/01



Photon analyses at CDF

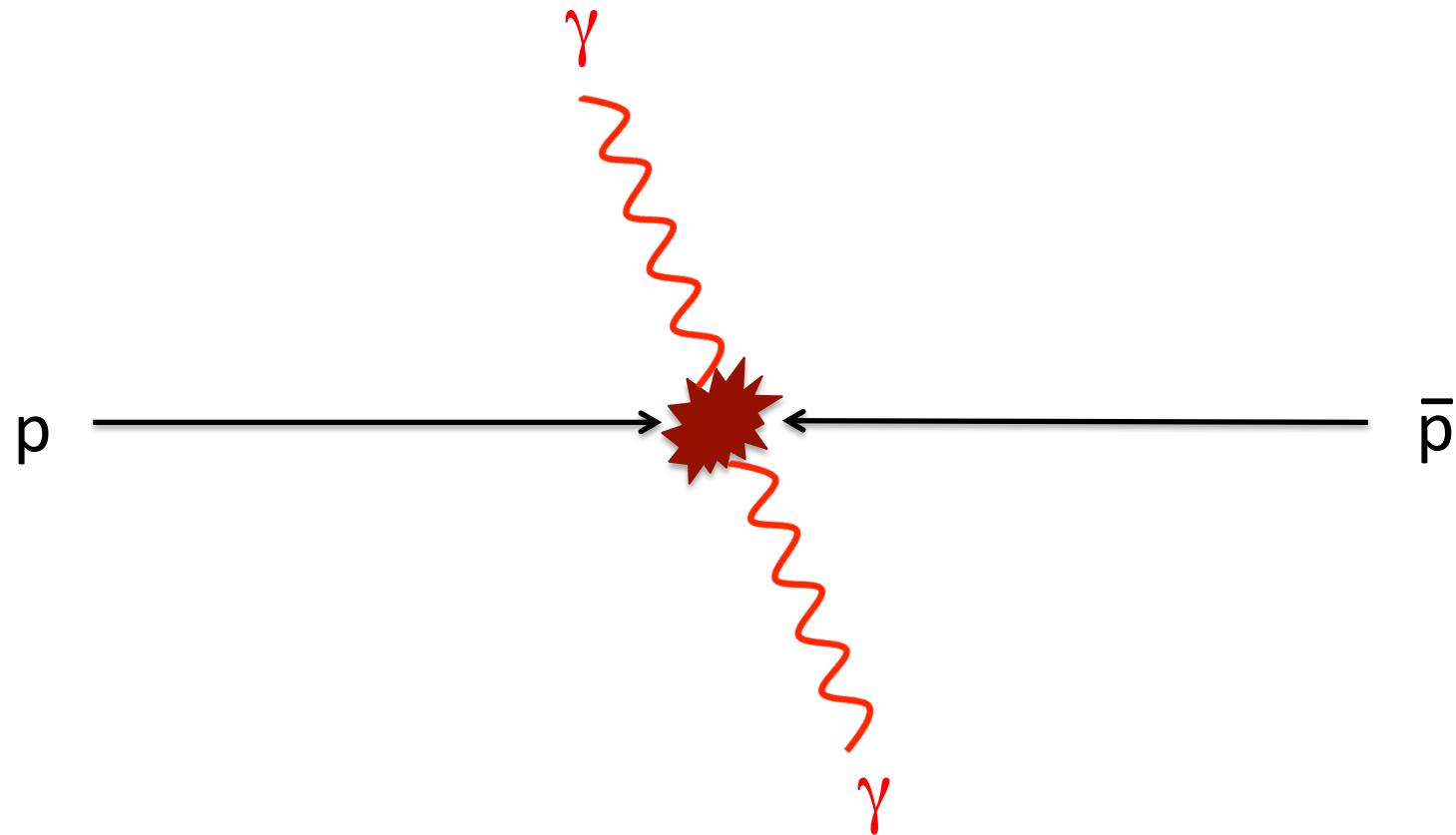
- Photon-related analyses have been hot topics at CDF
- We have published **~30** papers using CDF Run II data on a wide variety of photon-related topics.
 - QCD cross section measurements
 - Searches for new physics



Prompt γ production in hadron colliders

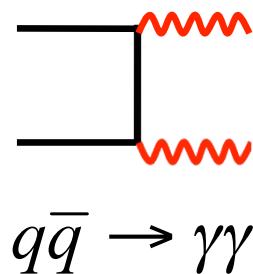
- Prompt photon production is a field of very high interest in hadron colliders.
 - A probe to search for **new phenomena** – *e.g.* $G^* \rightarrow \gamma\gamma$
 - The cleanest probe to test QCD predictions
 - Important for precision H measurements: $H \rightarrow \gamma\gamma$
- Today I will present two photon analyses using the full CDF II dataset.
 - **Diphoton** cross sections
 - **Photon+heavy flavor (b/c)** cross sections

Diphoton cross sections

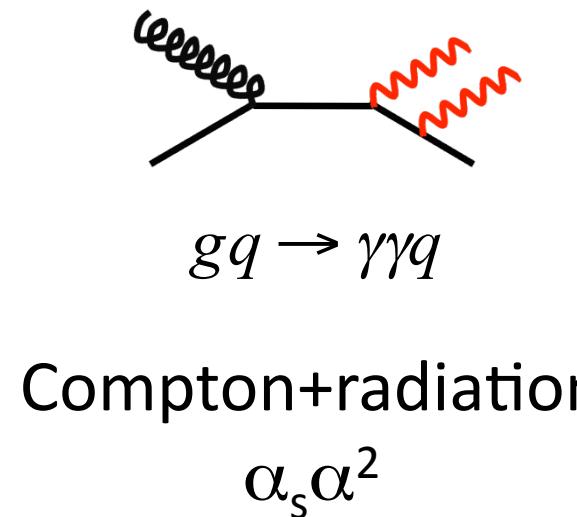


Prompt $\gamma\gamma$ production in hadron colliders

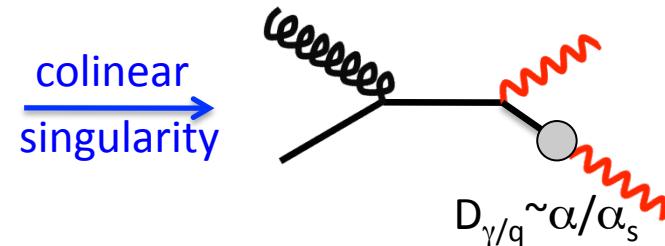
Hard QCD (“direct” $\gamma\gamma$ production):



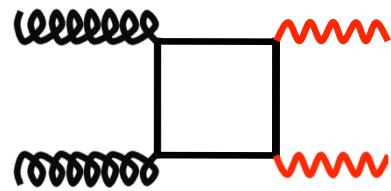
Born: α^2



Compton+radiation
 $\alpha_s \alpha^2$



Fragmentation: α^2
Suppressed by
isolation cut

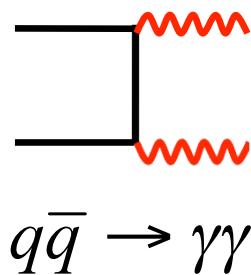


$gg \rightarrow \gamma\gamma$

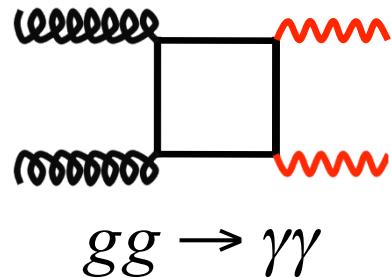
“Box”: Dominant
at the LHC

Prompt $\gamma\gamma$ production in hadron colliders

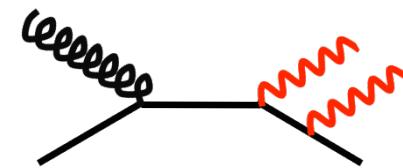
Hard QCD (“direct” $\gamma\gamma$ production):



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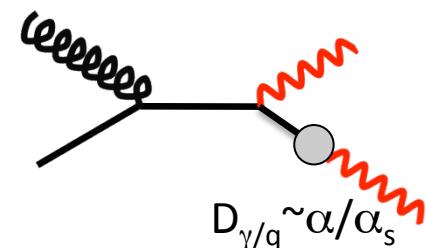


“Box”: Dominant
at the LHC



Compton+radiation
 $\alpha_s \alpha^2$

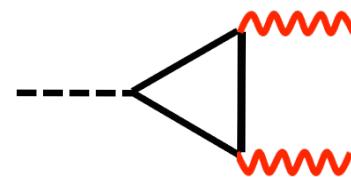
colinear
singularity



$$D_{\gamma/q} \sim \alpha/\alpha_s$$

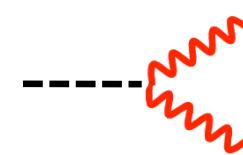
Fragmentation: α^2
Suppressed by
isolation cut

Possible heavy resonance decays:



$$H \rightarrow \gamma\gamma$$

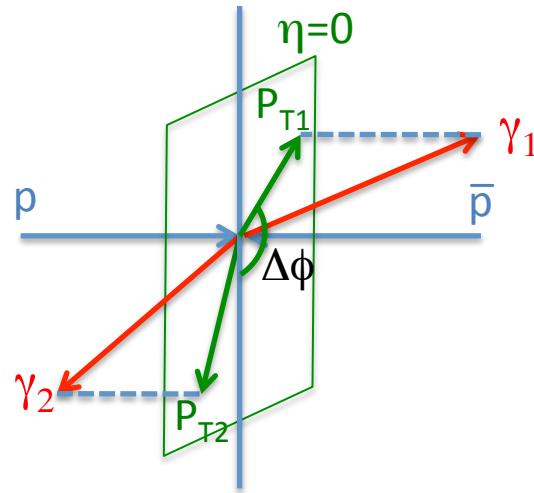
Higgs boson



$$G^* \rightarrow \gamma\gamma$$

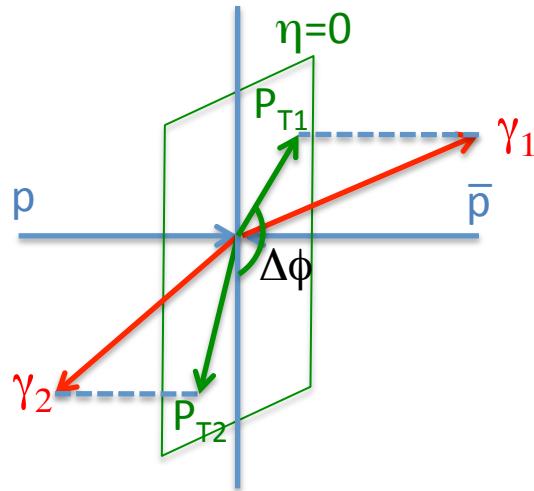
Extra dimensions

Interesting kinematic variables



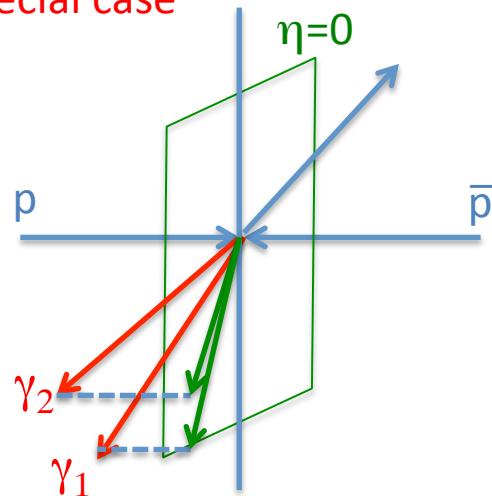
- $m(\gamma\gamma) = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$
 - Search for resonances.
- $P_T(\gamma\gamma) = |\vec{P}_{T1} + \vec{P}_{T2}|$
 - Sensitive to activity in the event.
- $\Delta\phi(\gamma\gamma)$
 - Sensitive to production mechanism.

Interesting kinematic variables



- $m(\gamma\gamma) = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$
 - Search for resonances.
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 - Sensitive to activity in the event.
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Special case

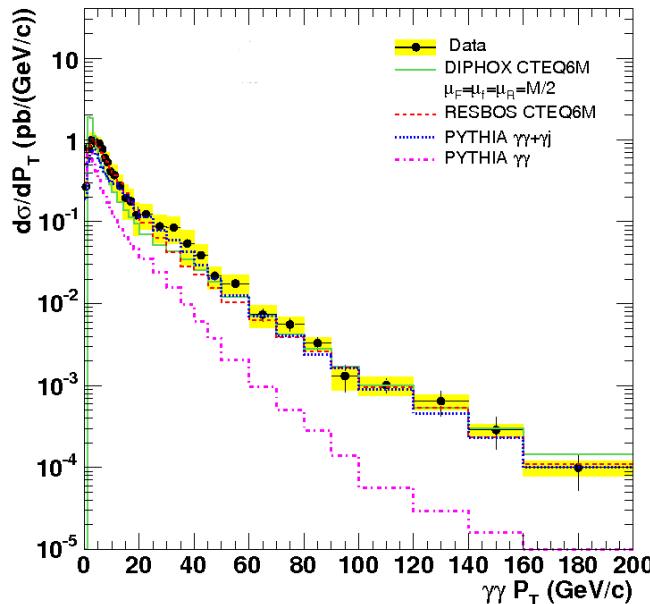
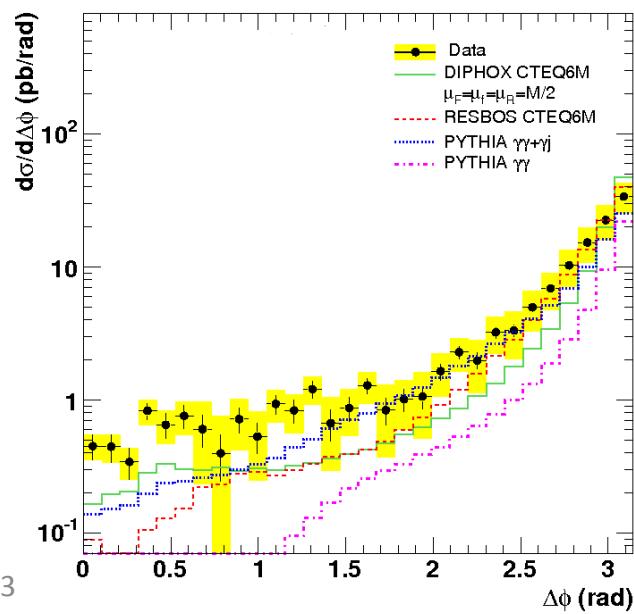
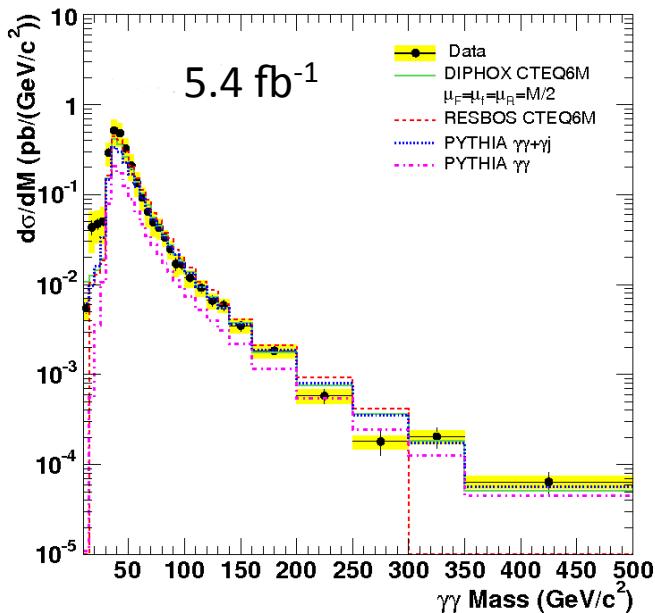


- Fragmentation/higher order diagrams
 - Two γ 's go almost collinear
 - Low $m(\gamma\gamma)$, intermediate $P_T(\gamma\gamma)$, low $\Delta\phi(\gamma\gamma)$
- Resummation
 - Low $P_T(\gamma\gamma)$, high $\Delta\phi(\gamma\gamma)$

Previously published results – CDF

PRL 107 (2011) 102003

PRD 84 (2011) 052006

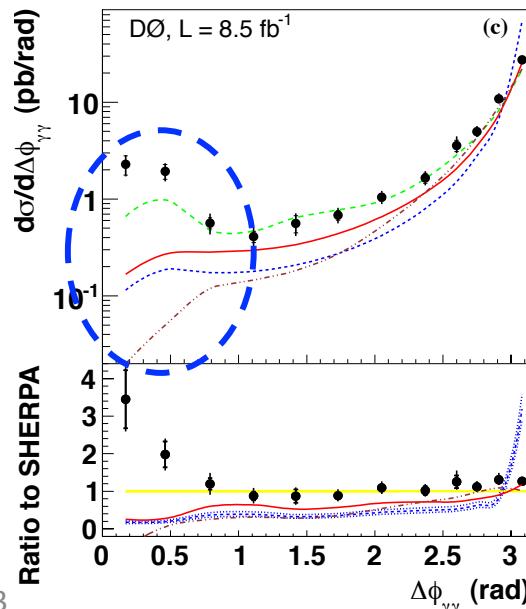
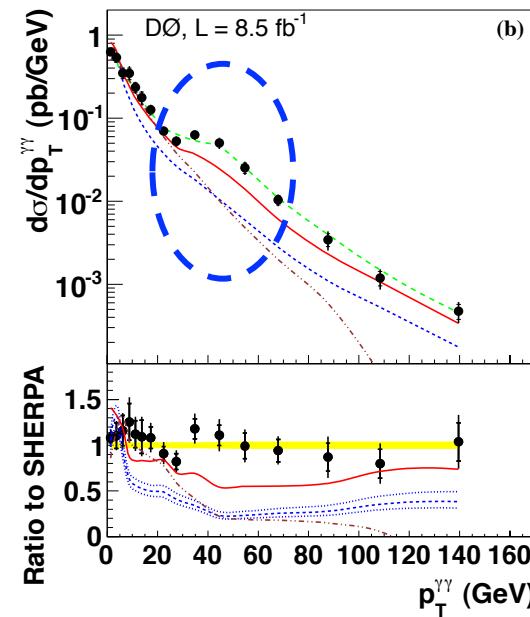
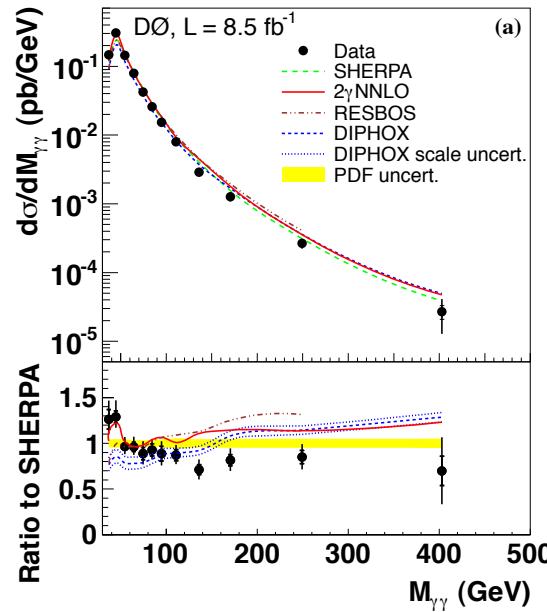


- Identified the importance of **resummation**, $q \rightarrow \gamma$ fragmentation and **parton-shower** in the modeling of diphoton cross sections.

Previously published results – D0

Full Run II data set

arXiv:1301.4536

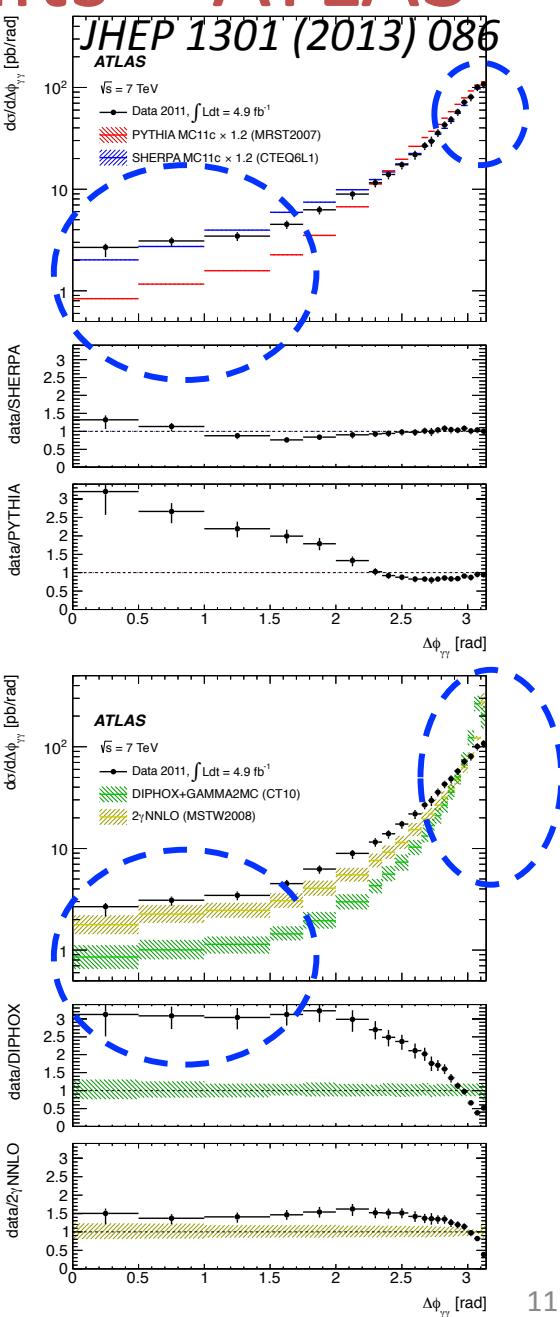
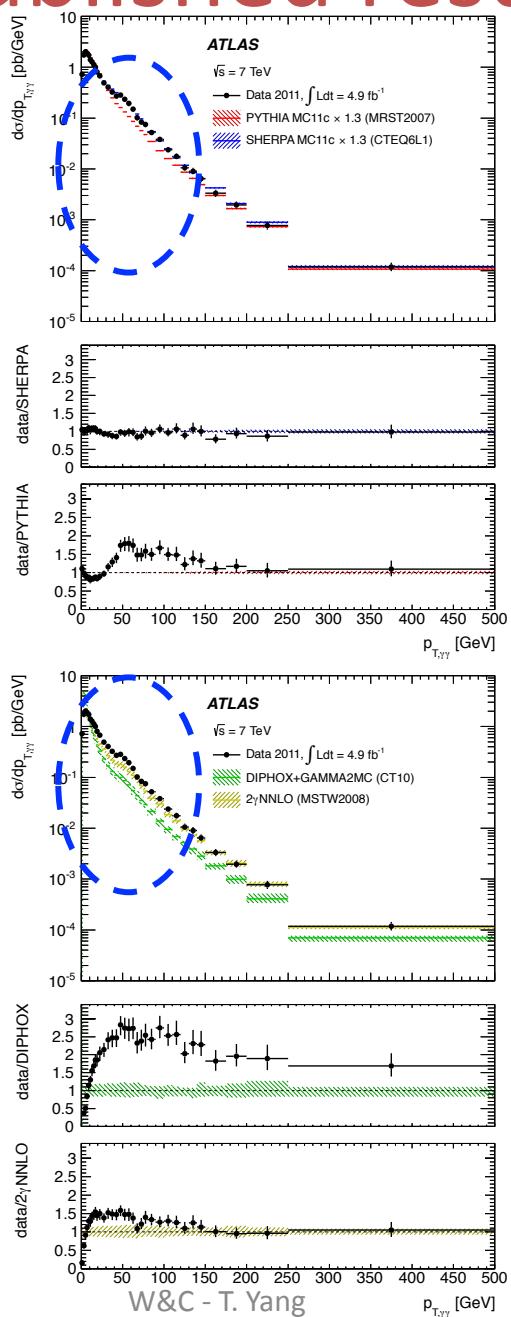
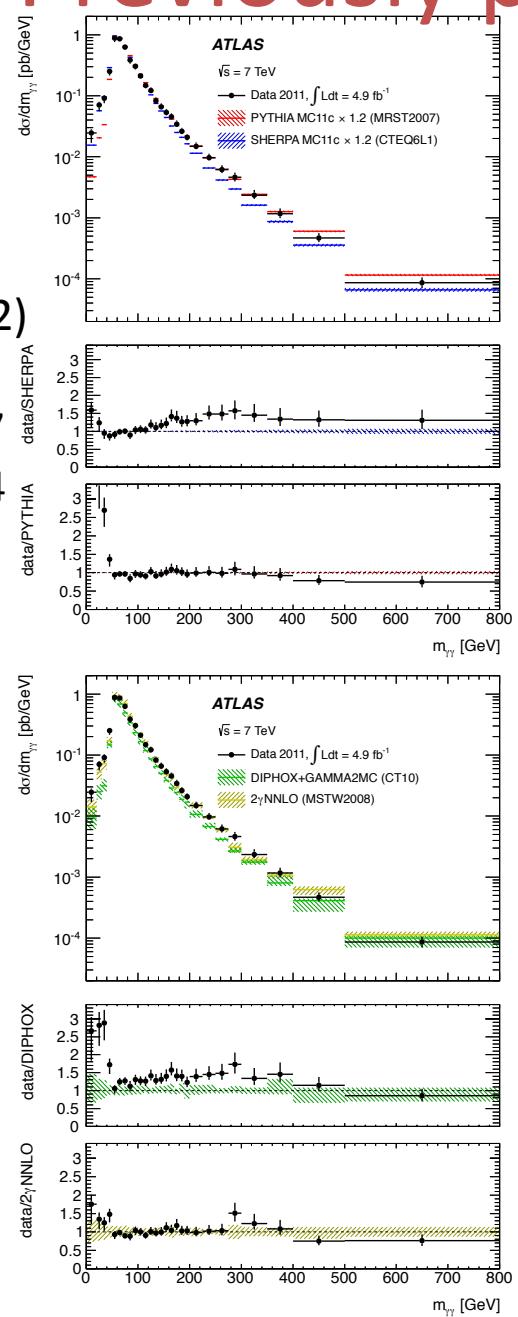


$$\begin{aligned} P_{T1(2)} > 18(17) \text{ GeV/c}, & |\eta_{1,2}| < 0.9 \\ \Delta R(\gamma, \gamma) > 0.4, & E_T^{\text{iso}} < 2.5 \text{ GeV} \end{aligned}$$

- Sherpa describes data the best in the intermediate $P_T(\gamma\gamma)$ and low $\Delta\phi_{\gamma\gamma}$ regions.

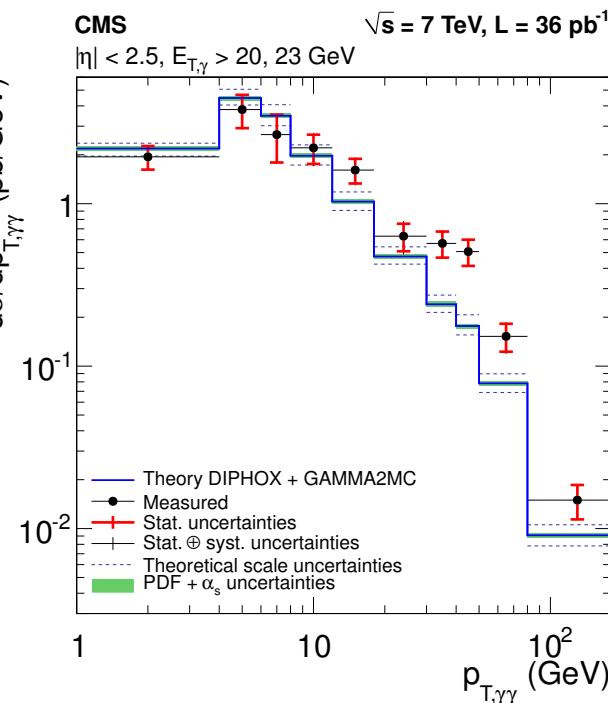
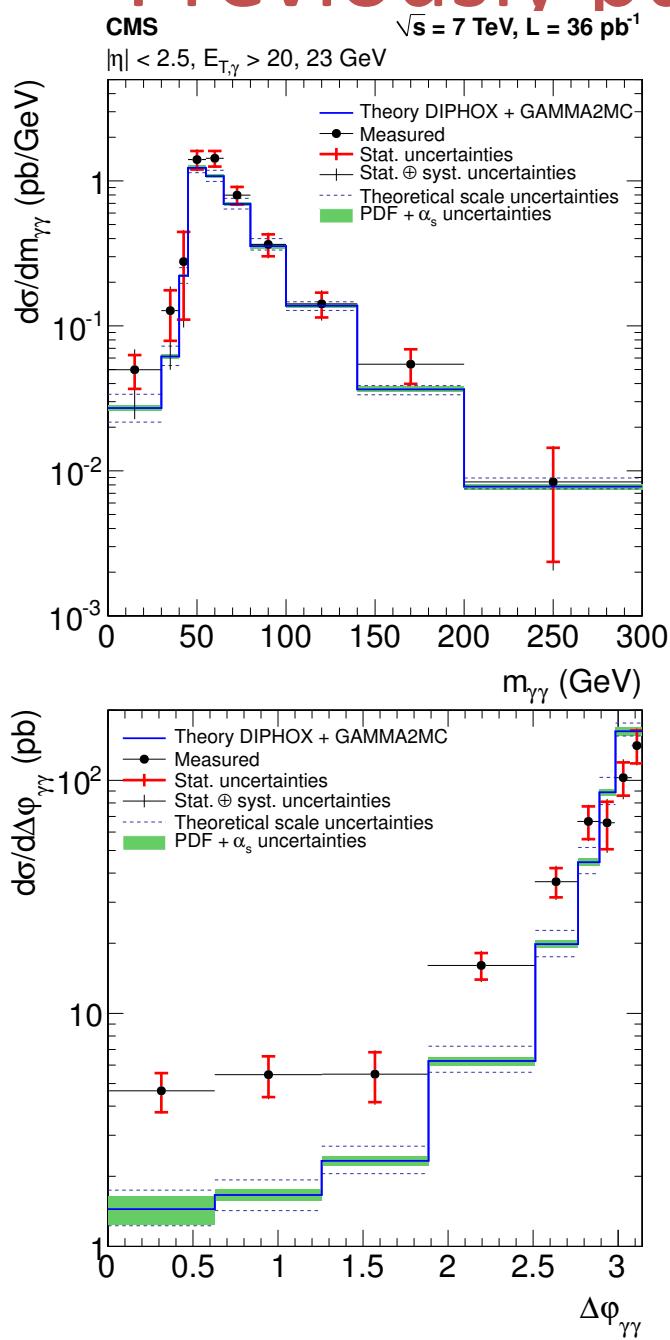
Previously published results – ATLAS

$P_{T(2)} > 25(22)$
 GeV/c,
 $|\eta_{1,2}| < 2.37$
 $\Delta R(\gamma, \gamma) > 0.4$



Previously published results – CMS

JHEP 1201 (2012) 133



- DIPHOX discrepancy for $P_T(\gamma\gamma) > 30 \text{ GeV}$ and $\Delta\phi(\gamma, \gamma) < \pi/2$

Updated diphoton cross section measurements

- Use the full 9.5 fb^{-1} CDF run II dataset.
- Select **isolated** diphoton events.
 - Background subtraction using **track isolation** information.
- **Pythia** evaluation of efficiency/acceptance/unfolding.
- Compare results with new predictions.

$$\frac{d\sigma}{dX} = \frac{N_{\gamma\gamma}}{\varepsilon \cdot A \cdot L \cdot \Delta}$$

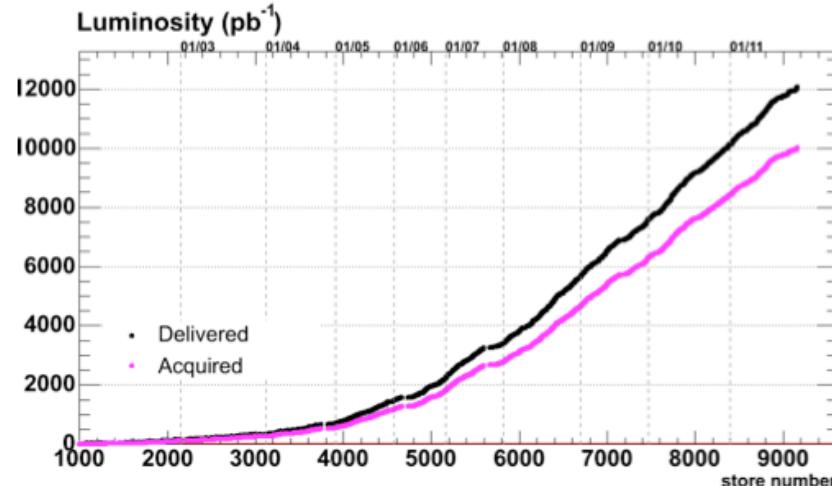
The Tevatron and CDF

Tevatron:

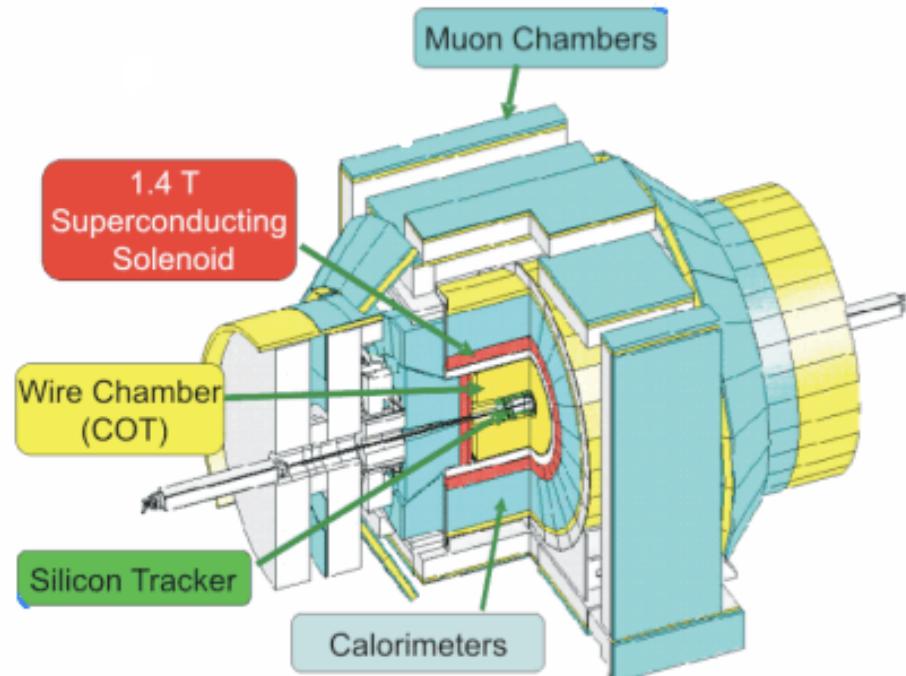
- Proton-antiproton accelerator
- $\sqrt{s} = 1.96 \text{ TeV}$
- Delivered $\sim 12 \text{ fb}^{-1}$
- Recorded $\sim 10 \text{ fb}^{-1}$ for each experiment

CDF

- Collider Detector at Fermilab
- Tracking (large B field):
 - Silicon tracking
 - Wire Chamber
- Calorimetry:
 - Electromagnetic (EM)
 - Hadronic
- Muon system

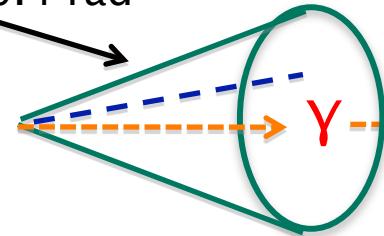


A big thank you to Accelerator Division!



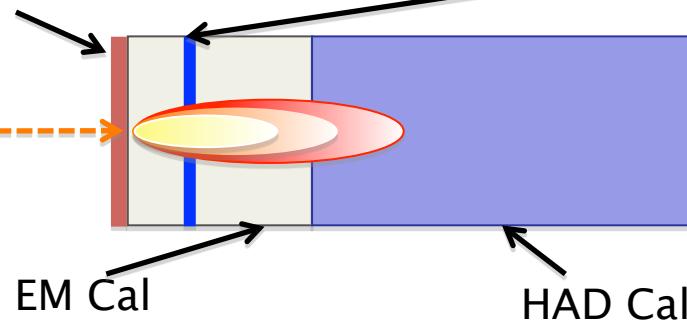
Photon identification and event selection

Isolation cone:
 $R=0.4$ rad



CP2: pre-shower

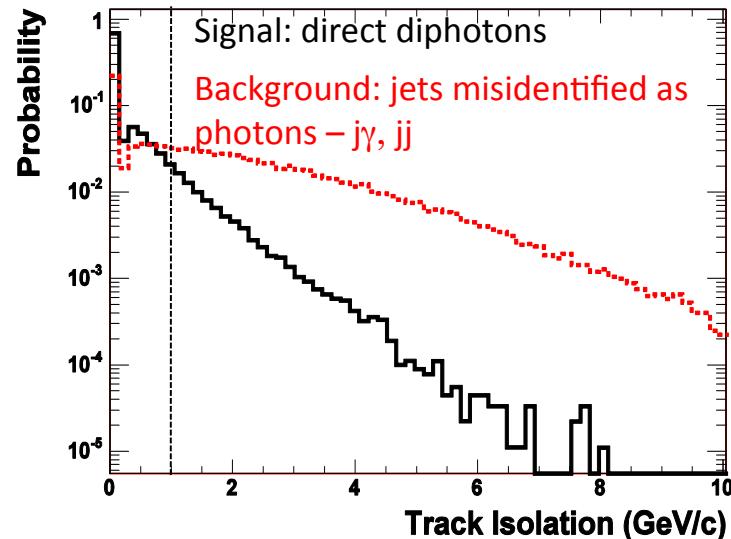
CES: shower maximum profile



- Used dedicated diphoton triggers with optimized efficiency
- Photons were selected offline from EM clusters, reconstructed in a cone of radius $R=0.4$ in the $\eta-\phi$ plane, and requiring:
 - Fiducial to the central calorimeter: $|\eta| < 1.1$
 - $E_T \geq 17, 15$ GeV ($\gamma\gamma$ events)
 - Isolated in the calorimeter: $I_{\text{cal}} = E_{\text{tot}}(R=0.4) - E_{\text{EM}}(R=0.4) \leq 2$ GeV
 - Low HAD fraction: $E_{\text{HAD}}/E_{\text{EM}} \leq 0.055 + 0.00045 \times E_{\text{tot}}/\text{GeV}$
 - At most one track in cluster with $p_T^{\text{trk}} \leq 1$ GeV/c + $0.005 \times E_T/\text{GeV}$
 - Shower profile consistent with predefined patterns: $\chi^2_{\text{CES}} \leq 20$
 - Only one high energy CES cluster: E_T of 2nd CES cluster ≤ 2.4 GeV + $0.01 \times E_T$

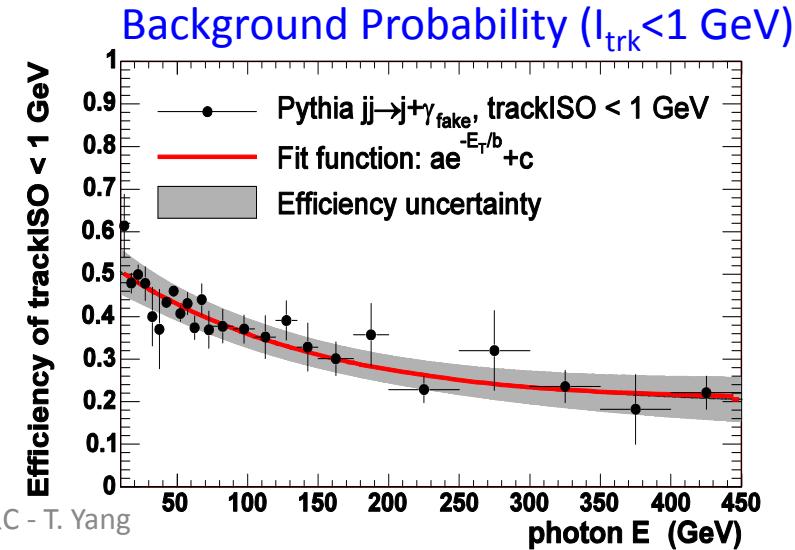
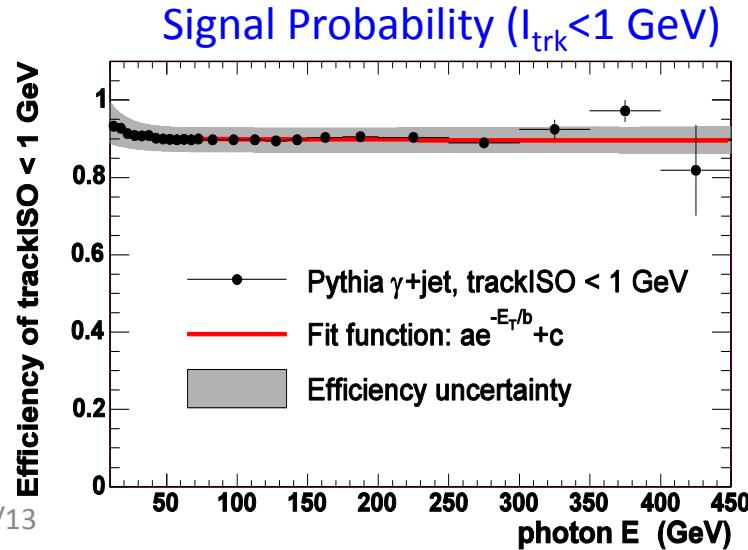
} Imply that
 $\Delta R(\gamma, \gamma)$ or $\Delta R(\gamma, j) \geq 0.4$

Background subtraction using track isolation



$$I_{trk} = \sum_{\substack{\text{tracks in } R < 0.4 \\ |z_{vtx} - z_{trk}| < 5\text{ cm}}} p_T^{trk}$$

- Sensitive only to underlying event and jet fragmentation (for fake γ)
- Immune to multiple interactions (due to z-cut) and calorimeter leakage
- Good resolution in low- E_T region, where background is most important
- Uses charged particles only



Background subtraction

- For a single γ , a weight can be defined to characterize it as signal or background:
 - $\varepsilon = 1 (0)$ if $|l_{\text{trk}}| < (\geq) 1 \text{ GeV}/c$
 - ε_s = signal probability for $|l_{\text{trk}}| < 1 \text{ GeV}/c$
 - ε_b = background probability for $|l_{\text{trk}}| < 1 \text{ GeV}/c$
- For $\gamma\gamma$, use the track isolation cut for each photon to compute a per-event weight under the different hypotheses ($\gamma\gamma$, $\gamma+\text{jet}$ and dijet):

$$w = \frac{\varepsilon - \varepsilon_b}{\varepsilon_s - \varepsilon_b}$$

$$\begin{pmatrix} w_{jj} \\ w_{j\gamma} \\ w_{\gamma j} \\ \textcolor{red}{w_{\gamma\gamma}} \end{pmatrix} = E^{-1} \times \begin{pmatrix} N_{ff} \\ N_{fp} \\ N_{pf} \\ N_{pp} \end{pmatrix}$$

Transfer matrix

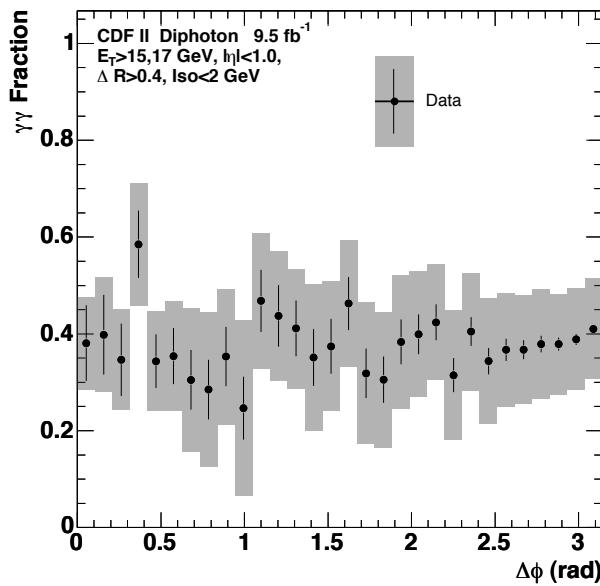
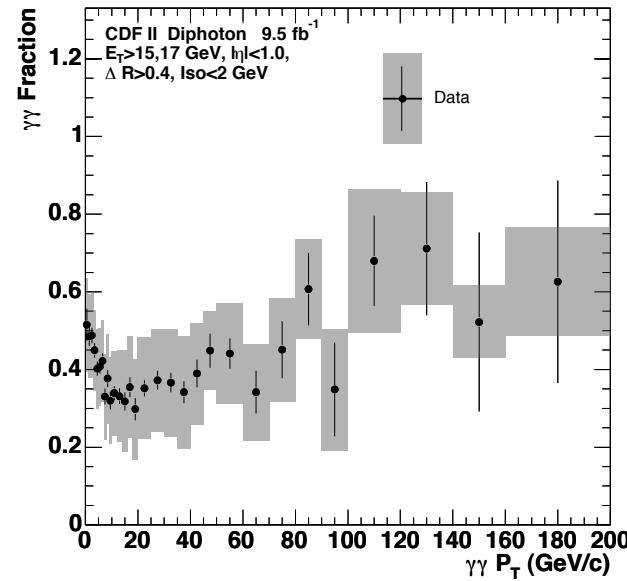
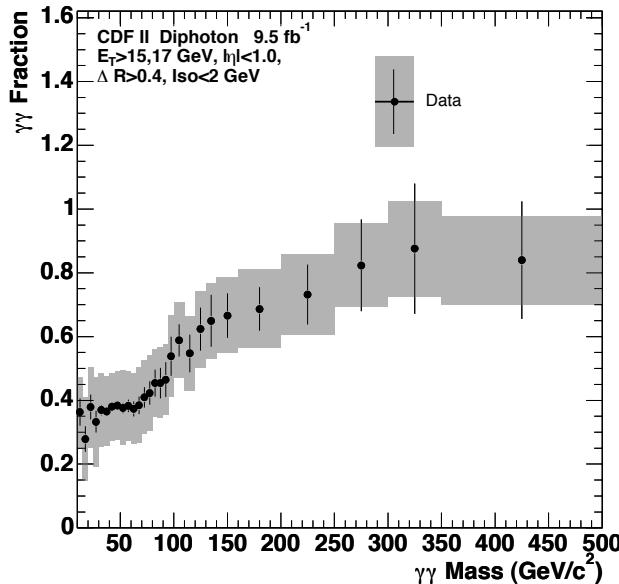
Both photons fail
Leading fail, trailing passes
Leading passes, trailing fails
Both photons pass

e.g. leading passes/trailing fails

$$\begin{pmatrix} N_{ff} \\ N_{fp} \\ N_{pf} \\ N_{pp} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix}$$

Signal fractions

$$\text{Signal fraction} = \frac{N_{\gamma\gamma}}{N_{\text{data}}}$$



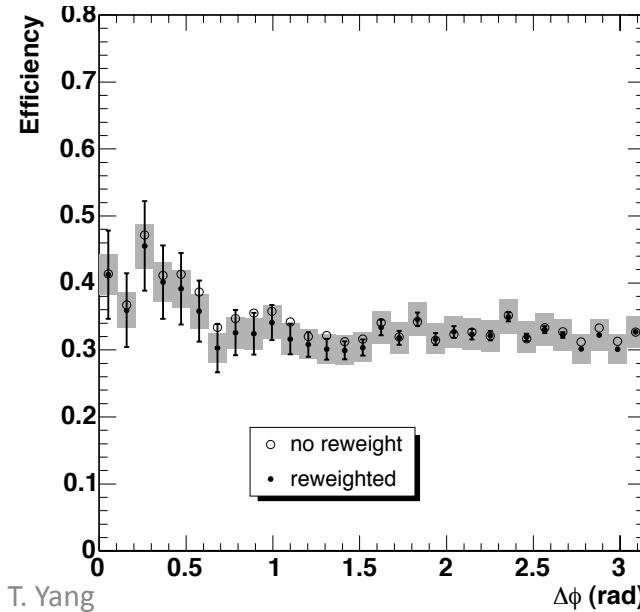
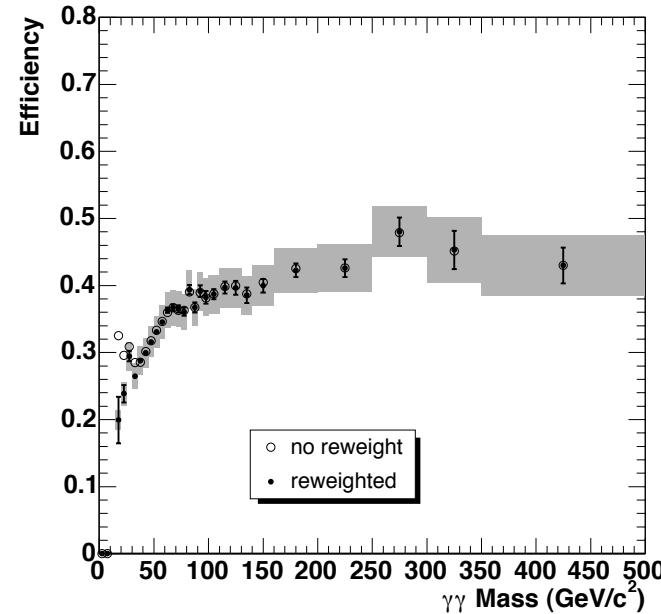
- Average ~40%
- Better at high mass:
 - 60-80% for $m(\gamma\gamma) \sim 80-150 \text{ GeV}/c^2$
 - ~80% for $m(\gamma\gamma) > 150 \text{ GeV}/c^2$
- Better at high $P_T(\gamma\gamma)$:
 - ~70% for $P_T(\gamma\gamma) > 100 \text{ GeV}/c$
- 15-30% sys. errors

Efficiency×Acceptance

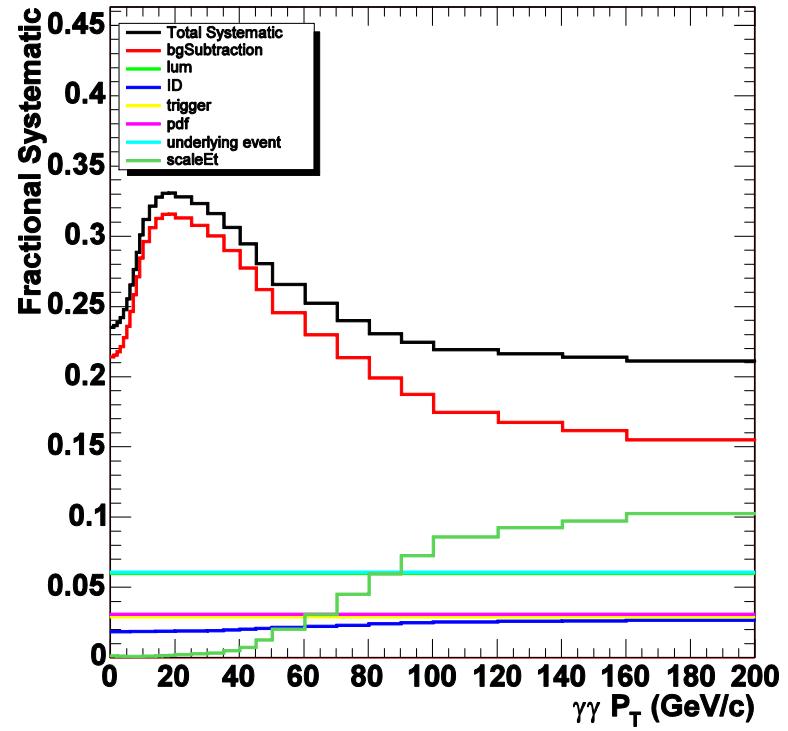
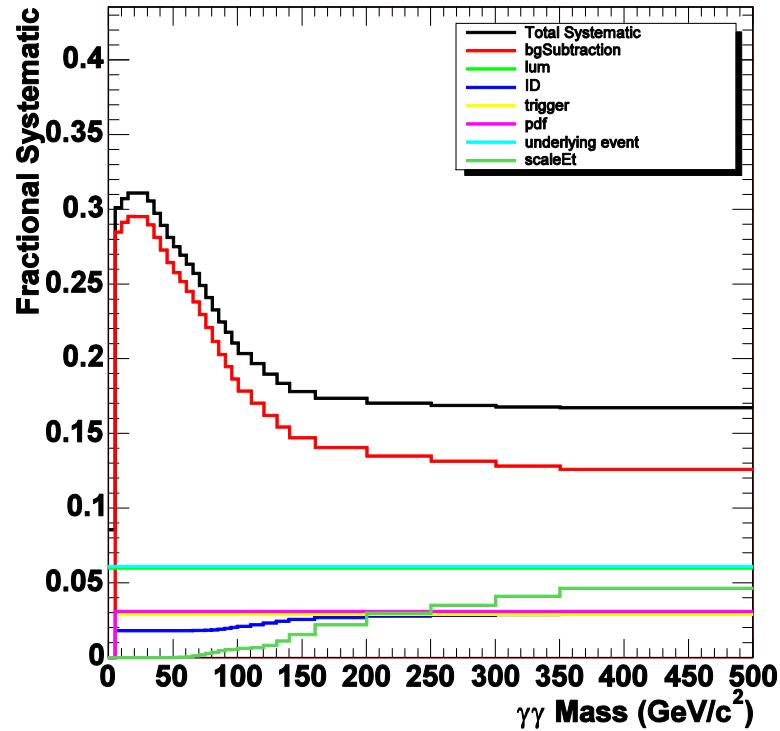
- Estimated using detector- and trigger-simulated and reconstructed PYTHIA events
- Procedure iterated to match PYTHIA kinematics to the data

Uncertainties in the efficiency estimation:

- 3% from material uncertainty
- 1.5% from the EM energy scale
- 3% from trigger efficiency uncertainty
- 6% (3% per photon) from underlying event (UE) correction
- Total systematic uncertainty: ~7-15%



Experimental systematic uncertainties



- Total systematic uncertainty $\sim 15\text{-}30\%$, smoothly varying with the kinematic variables considered
- Main source is background subtraction, followed by overall normalization (efficiencies: 7%; integrated luminosity: 6%; UE correction: 6%)

Theoretical predictions

- **PYTHIA** LO parton-shower calculation – including $\gamma\gamma$ and γj with radiation [T. Sjöstrand *et al.*, Comp. Phys. Comm. **135**, 238 (2001)]
- **SHERPA** LO parton-shower calculation with improved matching between hard and soft physics [T. Gleisberg *et al.*, JHEP **02**, 007 (2009)]
- **MCFM**: Fixed-order NLO calculation including non-perturbative fragmentation at LO [J. M. Campbell *et al.*, Phys. Rev. D **60**, 113006 (1999)]
- **DIPHOX**: Fixed-order NLO calculation including non-perturbative fragmentation at NLO [T. Binoth *et al.*, Phys. Rev. D **63**, 114016 (2001)]
- **RESBOS**: Low- P_T analytically resummed calculation matched to high- P_T NLO [T. Balazs *et al.*, Phys. Rev. D **76**, 013008 (2007)]
- **NNLO** calculation with q_T subtraction [L. Cieri *et al.*, <http://arxiv.org/abs/1110.2375> (2011)]

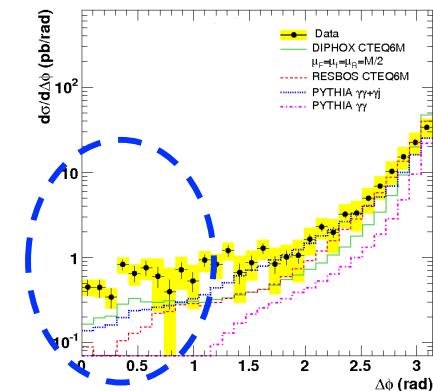
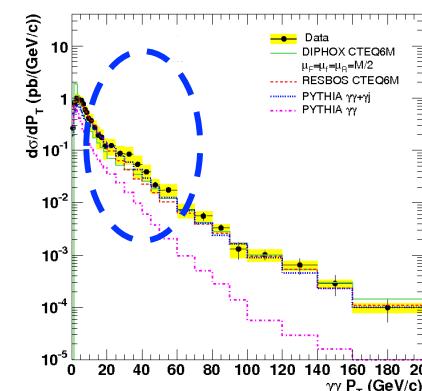
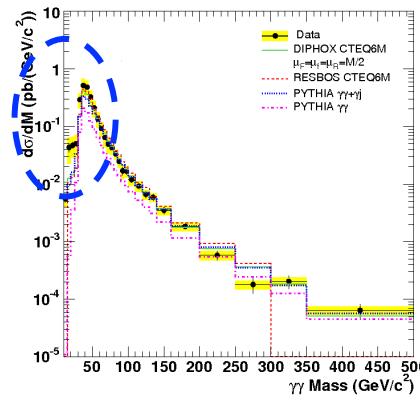
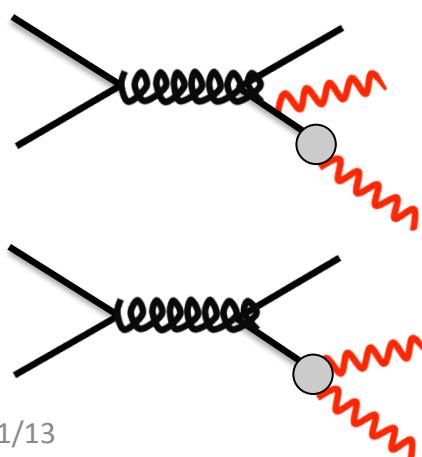
Theoretical predictions

- **PYTHIA** LO parton-shower calculation – including $\gamma\gamma$ and γj with radiation
[T. Sjöstrand *et al.*, Comp. Phys. Comm. **135**, 238 (2001)]

	Integrated cross section (pb)	Method
• SHERPA : LO parton-shower calculation including hard and soft physics	12.3 \pm 0.2 _{stat} \pm 3.5 _{syst}	Data (CDF)
• MCFM : Fixed-order NLO calculation at LO [J. M. Cacciari <i>et al.</i> , RESBOS]	11.3	DIPHOX
• DIPHOX : Fixed-order NLO calculation at NLO [T. Binoth <i>et al.</i> , MCFM]	10.6	SHERPA
• PYTHIA : LO parton-shower calculation including hard and soft physics	11.5	PYTHIA $\gamma\gamma + \gamma j$
• RESBOS : Low-energy NNLO calculation [T. Balazs <i>et al.</i> , Phys. Rev. D 76 , 013008 (2007)]	12.4	NNLO
• NNLO calculation with q_T subtraction [L. Cieri <i>et al.</i> , http://arxiv.org/abs/1110.2375 (2011)]	9.2	NLO

Collinear diphoton production

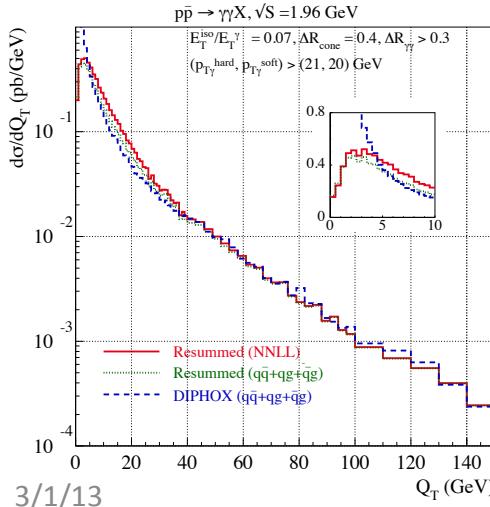
- **Fragmentation** – non-perturbative feature
 - The pQCD cross section is divergent when q and γ are collinear
 - Handled with a fragmentation function – **MCFM**, **DIPHOX**
 - Affect the low $m(\gamma\gamma)$, intermediate $P_T(\gamma\gamma)$ and low $\Delta\phi_{\gamma\gamma}$ regions
- Higher order corrections also contribute to the same regions – **SHERPA**, **NNLO**



Resummation

- Remove singularities [$P_T(\gamma\gamma) \rightarrow 0$] by adding initial gluon radiation
 - **RESBOS**: Low- P_T analytically resummed calculation matched to high- P_T NLO
 - **PYTHIA** and **SHERPA**: Use parton showering to add gluon radiation in a Monte Carlo simulation framework which effectively resums the cross section
 - Affects low $P_T(\gamma\gamma)$ and $\Delta\phi_{\gamma\gamma} = \pi$ regions

PRD 76, 013009 (2007)



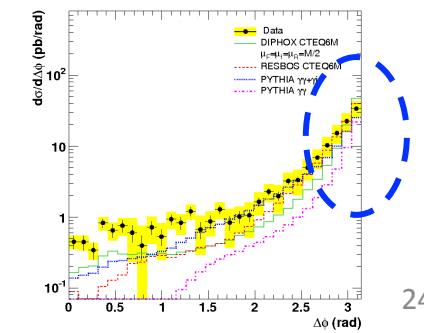
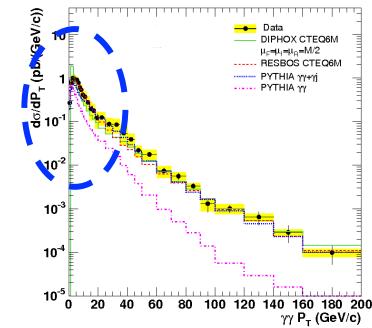
3/1/13

Fixed-order calculation contains singular terms at $P_T(\gamma\gamma) \rightarrow 0$ and $M(\gamma\gamma) \neq 0$ of the form

$$\frac{\alpha_s^n}{P_T^2(\gamma\gamma)} \ln^m \frac{M^2(\gamma\gamma)}{P_T^2(\gamma\gamma)} \quad \text{or} \quad -\alpha_s^n \delta(P_T(\gamma\gamma))$$

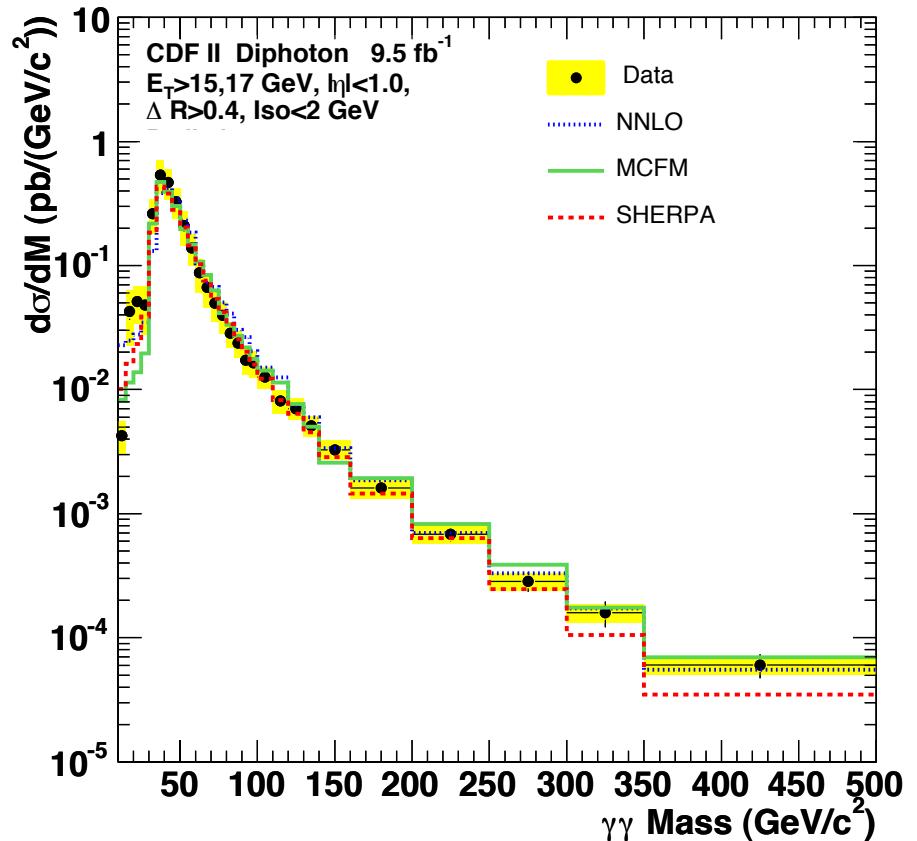
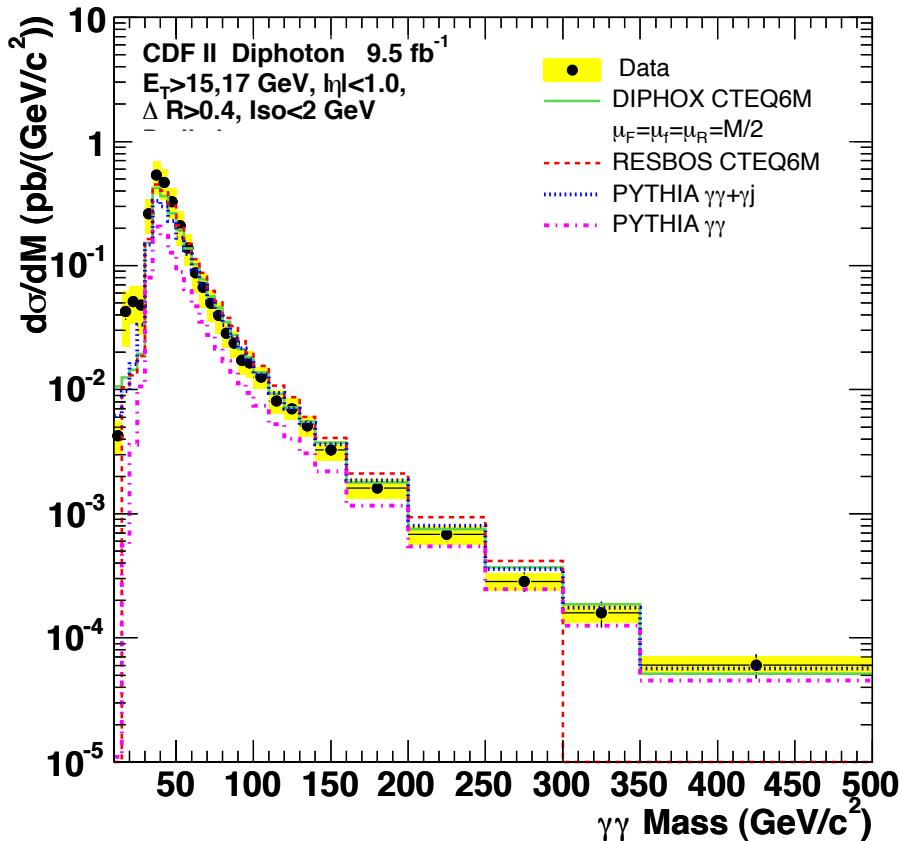
$$n = 1, \dots, \infty \quad m = 0, \dots, 2n - 1$$

W&C - T. Yang



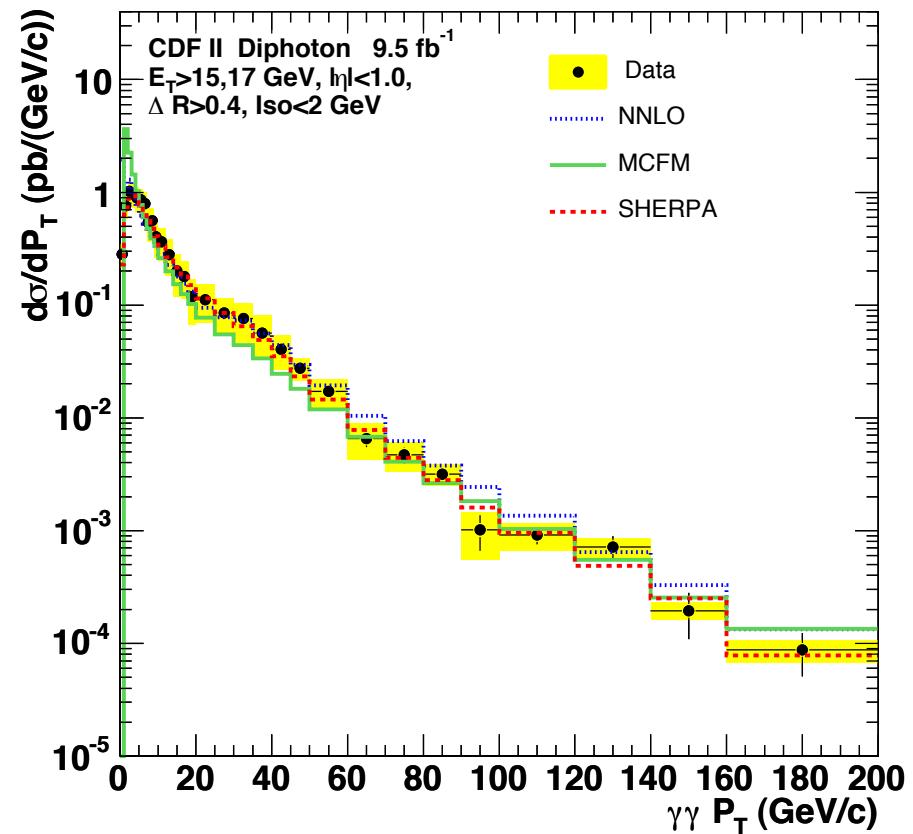
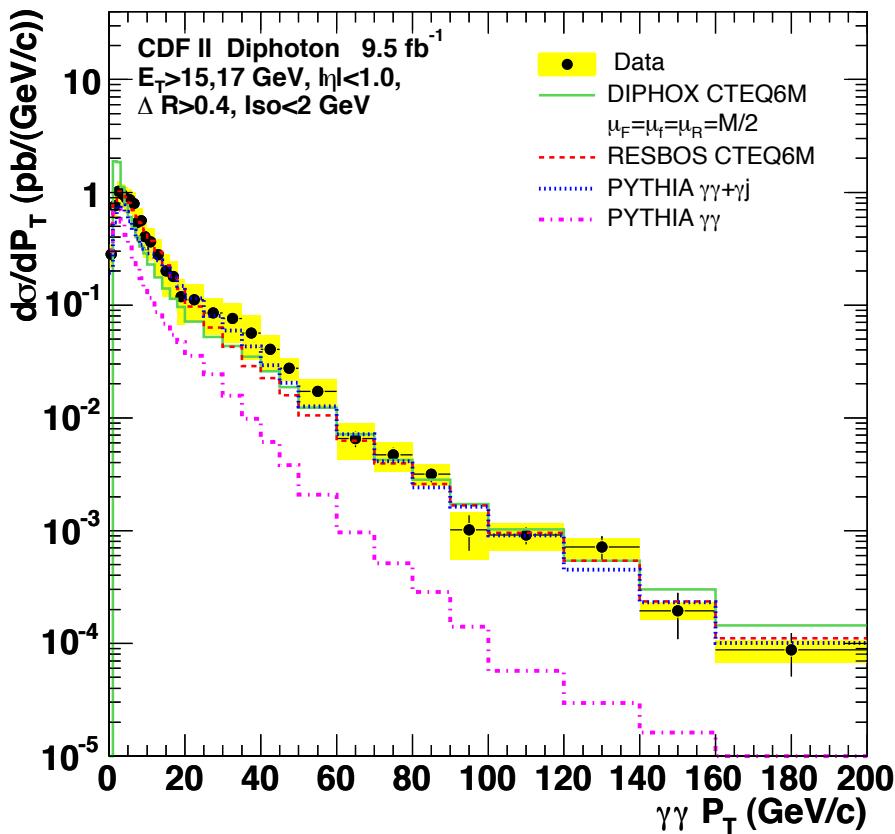
24

m($\gamma\gamma$)



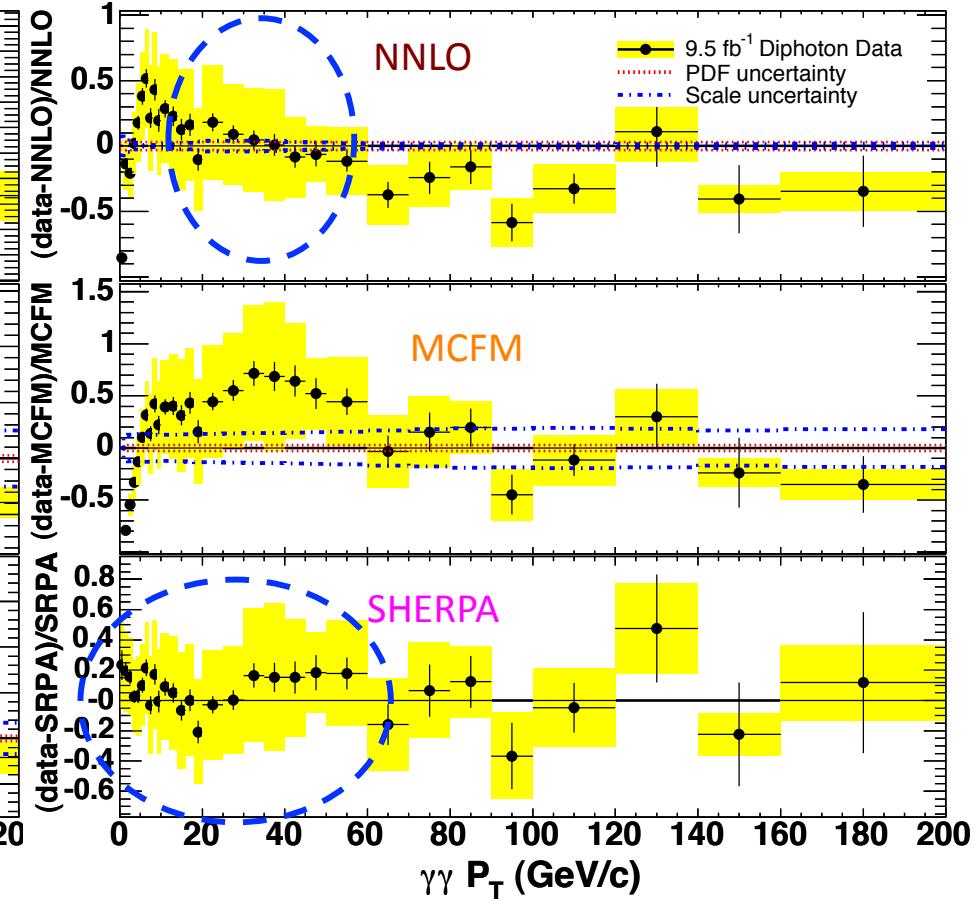
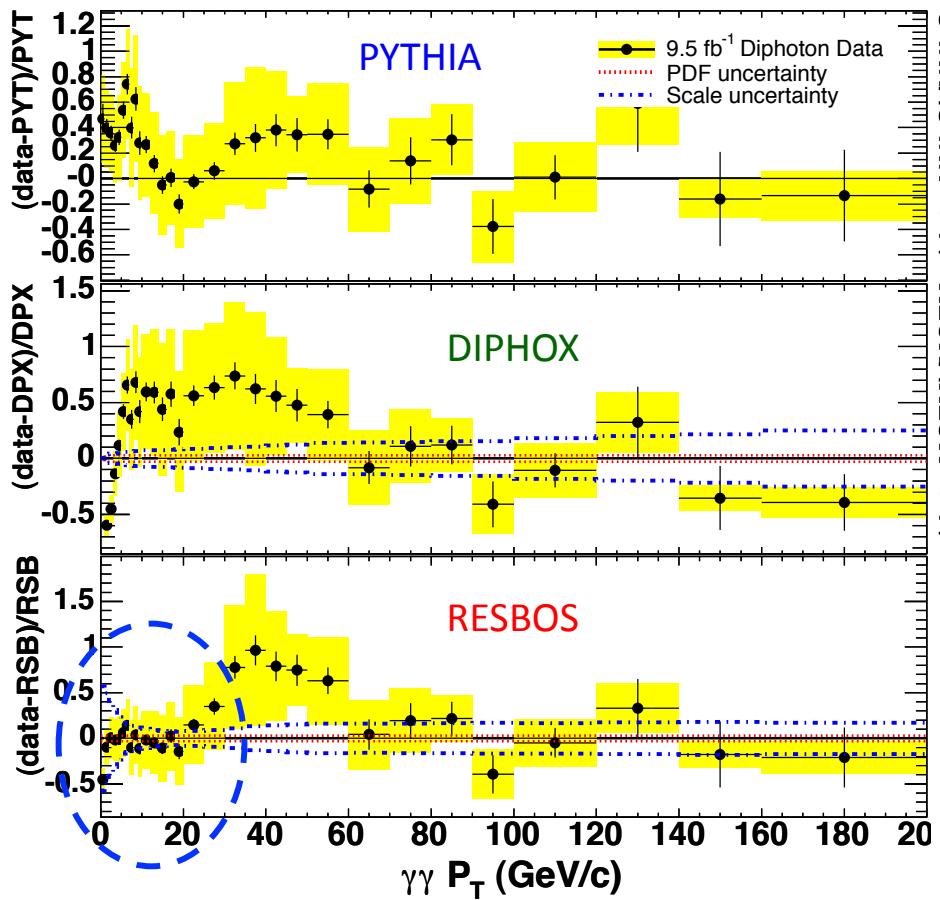
- Good agreement between data and theory for $M_{\gamma\gamma} > 30 \text{ GeV}/c^2$ except PYTHIA $\gamma\gamma$

$P_T(\gamma\gamma)$



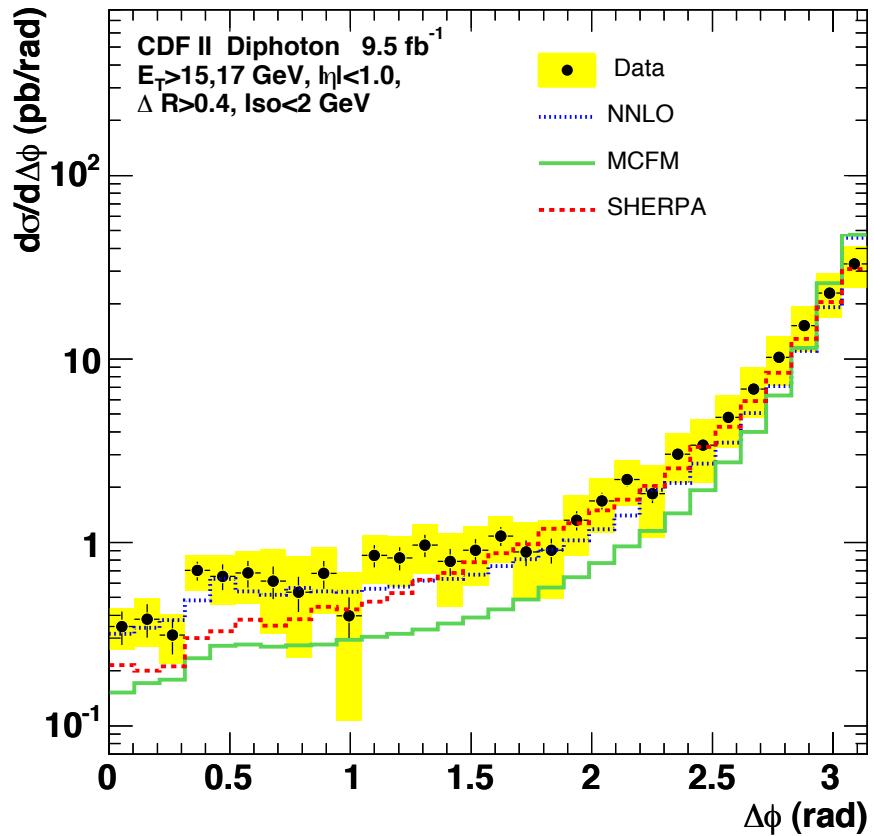
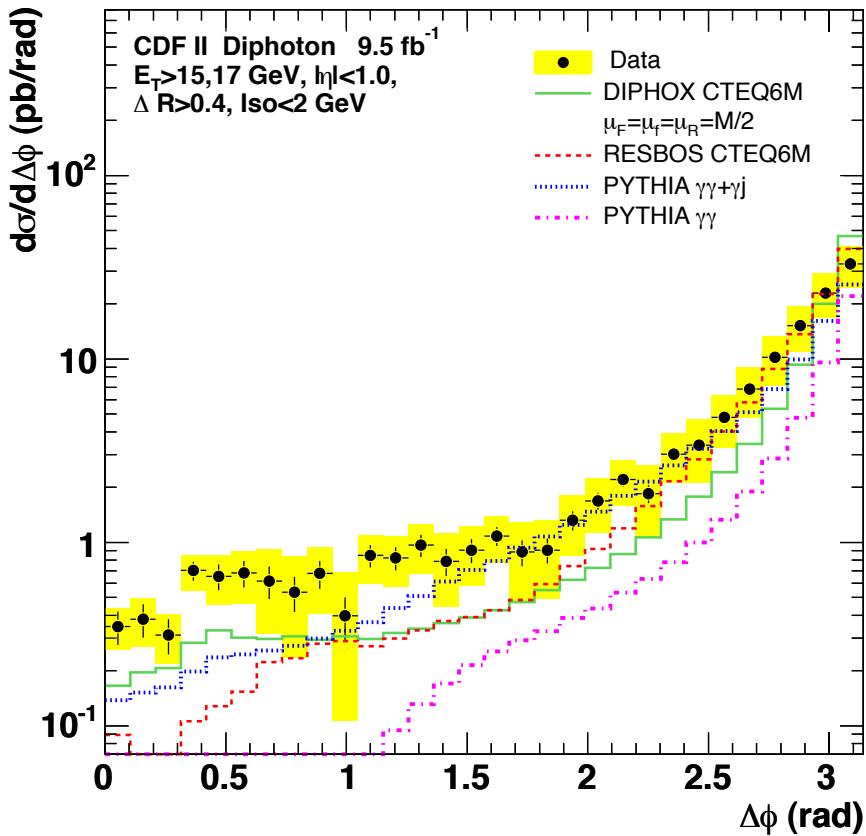
$P_T(\gamma\gamma)$ - ratios

NB: Vertical axis scales are not the same



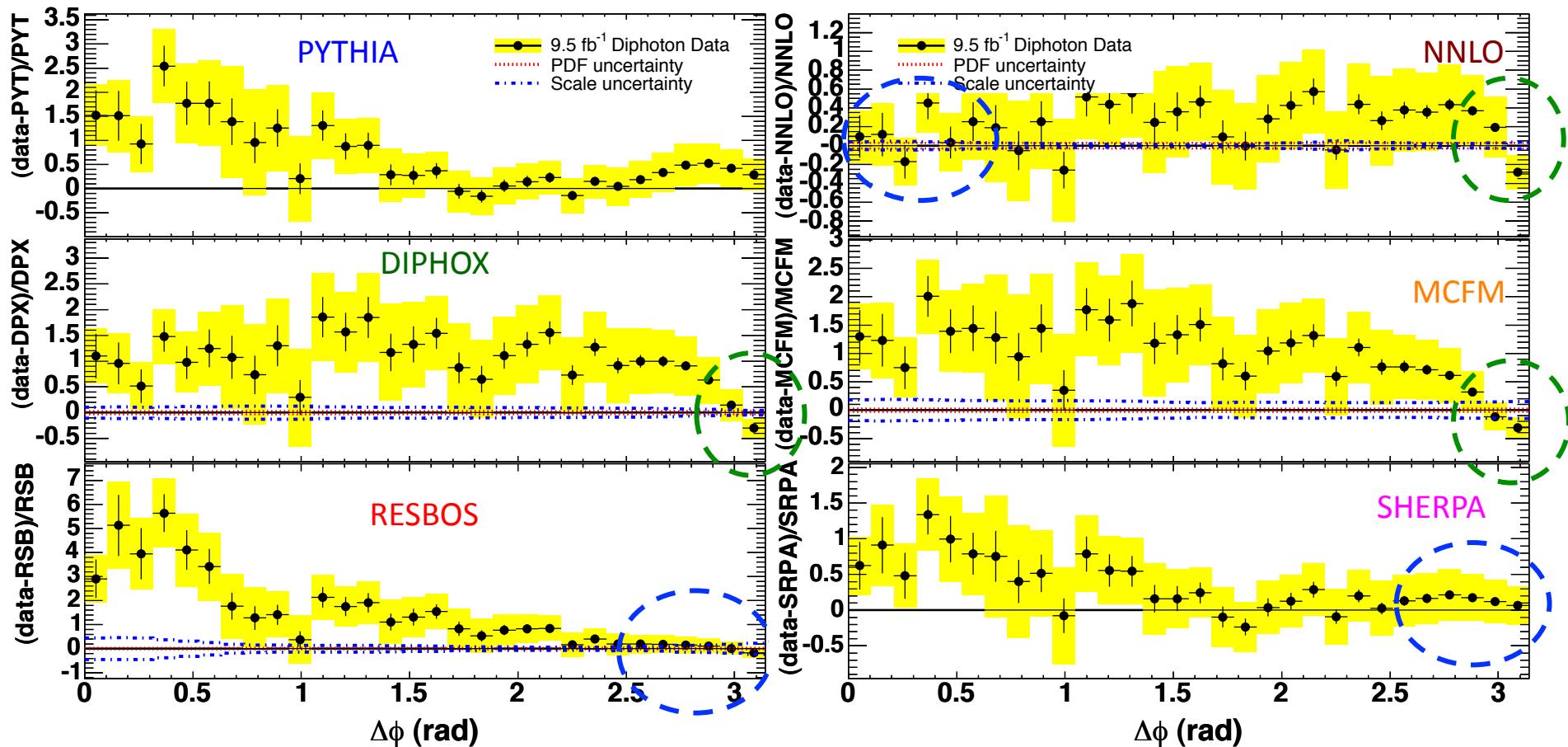
- RESBOS agrees with low $P_T(\gamma\gamma)$ data the best
- SHERPA agrees with low $P_T(\gamma\gamma)$ data well
- NNLO and SHERPA describe the “shoulder” of the data at $P_T(\gamma\gamma) = 20 - 50$ GeV/c (the “Guillet shoulder”)

$\Delta\phi(\gamma\gamma)$



$\Delta\phi(\gamma\gamma)$ - ratios

NB: Vertical axis scales are not the same

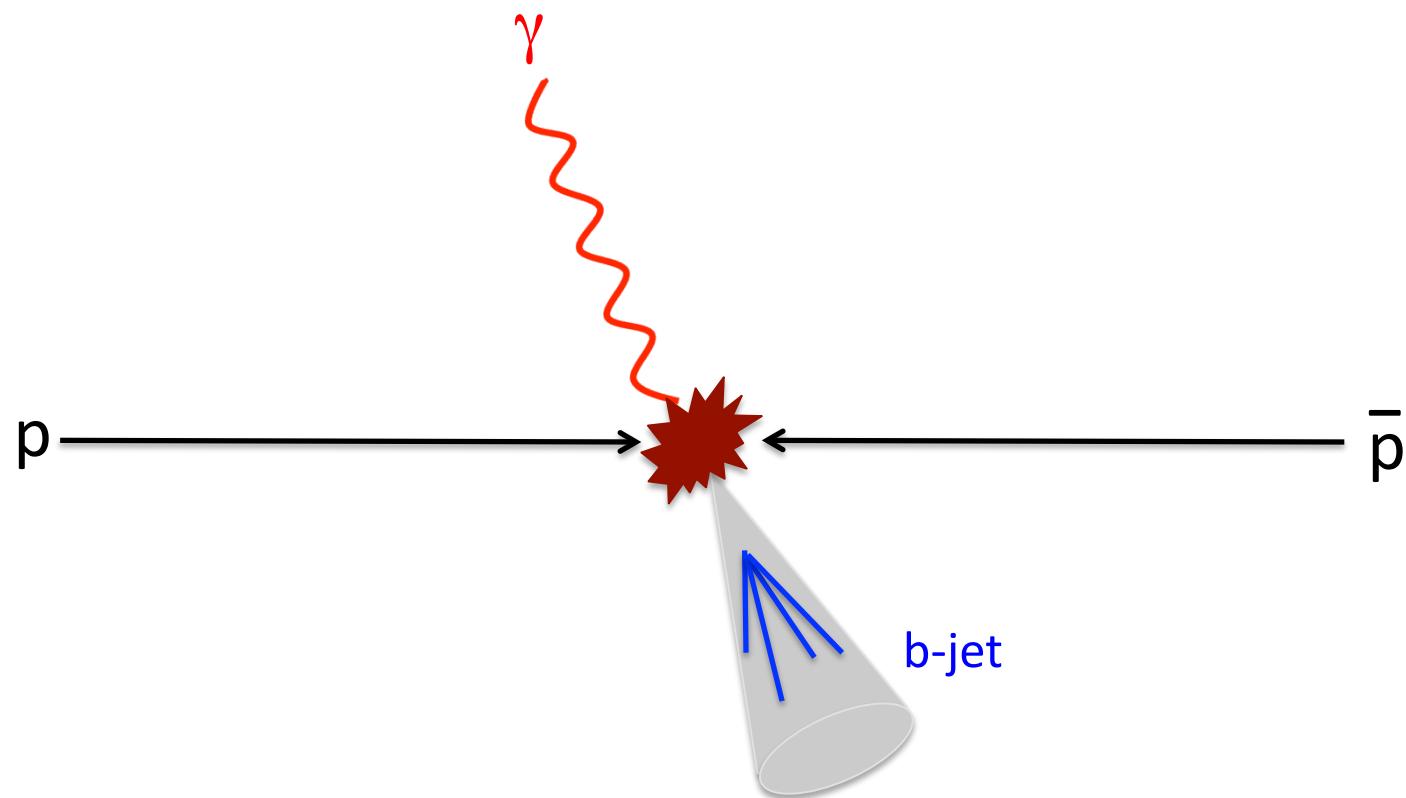


- RESBOS and SHERPA describe $\Delta\phi(\gamma\gamma) = \pi$
- Fixed order calculations do not describe $\Delta\phi(\gamma\gamma) = \pi$ as well
- NNLO describes $\Delta\phi(\gamma\gamma) = 0$

Summary of diphoton cross sections

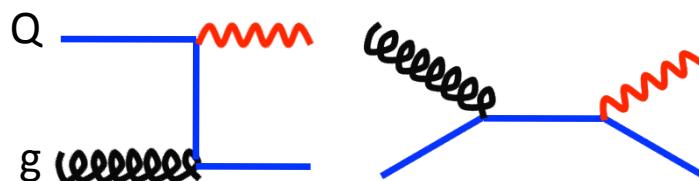
- High precision $\gamma\gamma$ cross sections are measured using the full CDF Run II dataset.
- The data are compared with parton shower, fixed-order and analytically resummed NLO, as well as NNLO calculations.
- The **SHERPA** calculation, overall, provides good description of the data, but still is somewhat low in regions sensitive to nearly collinear $\gamma\gamma$ emission (very low mass, very low $\Delta\phi$).
- The **RESBOS** calculation provides the best description of the data at low P_T and large $\Delta\phi$, where resummation is important, but fails in regions sensitive to nearly collinear $\gamma\gamma$ emission.
- The **NNLO** calculation provides the best description of the data at low $\Delta\phi$, but still not very good at very low mass and at high P_T .
- Paper accepted by PRL: arXiv:1212.4204

Photon+heavy flavor (b/c) cross sections

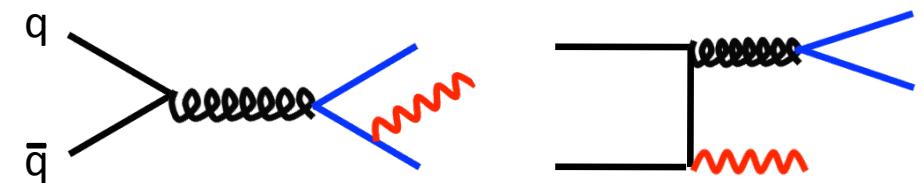


$\gamma+b/c+X$ production

- Photon produced in association with heavy quarks provides valuable information about PDFs of the initial state hadrons.
 - LO contribution: Compton scattering ($Qg \rightarrow Q\gamma$) dominates at low photon p_T .
 - NLO contribution: annihilation ($q\bar{q} \rightarrow Q\bar{Q}\gamma$) dominates at high photon p_T .



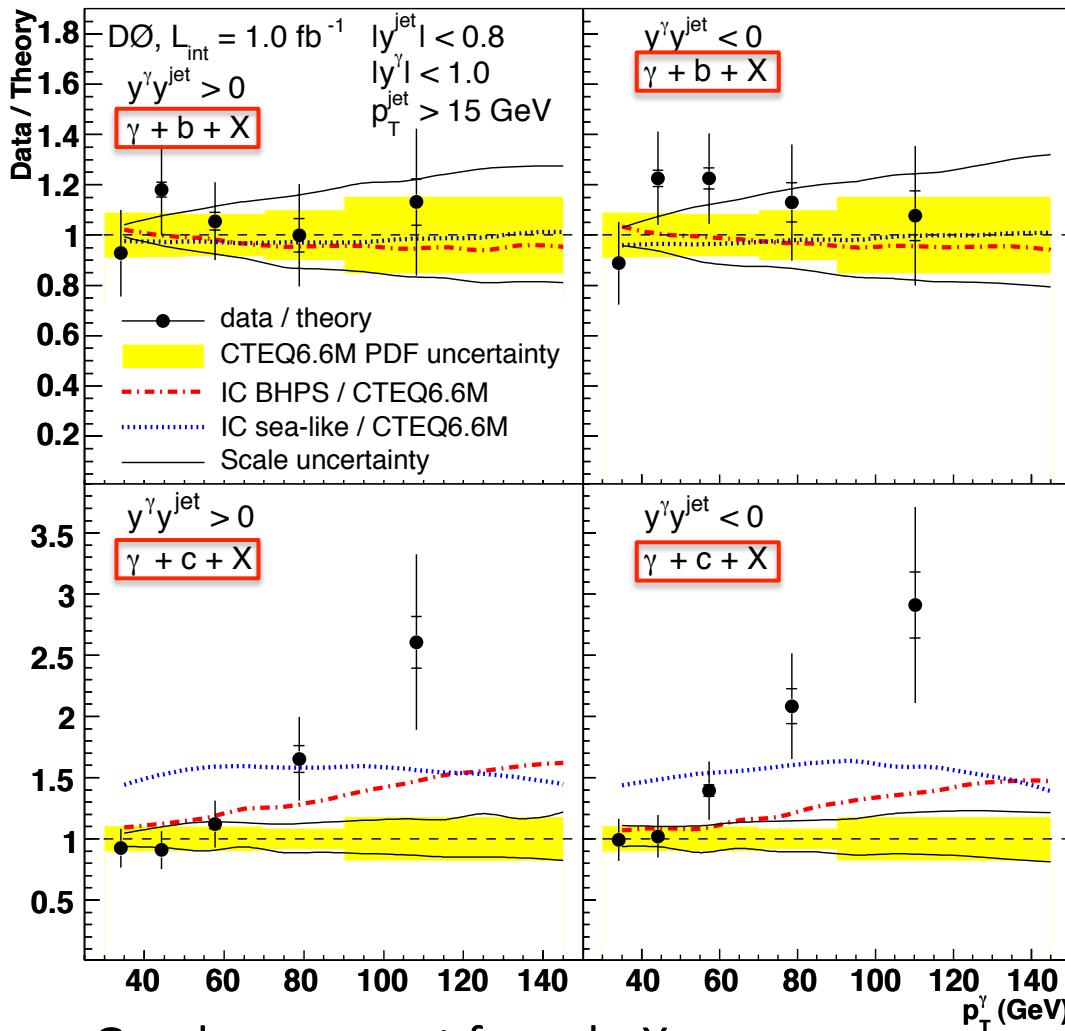
Compton scattering $\sim \alpha\alpha_s$



Annihilation $\sim \alpha\alpha_s^2$

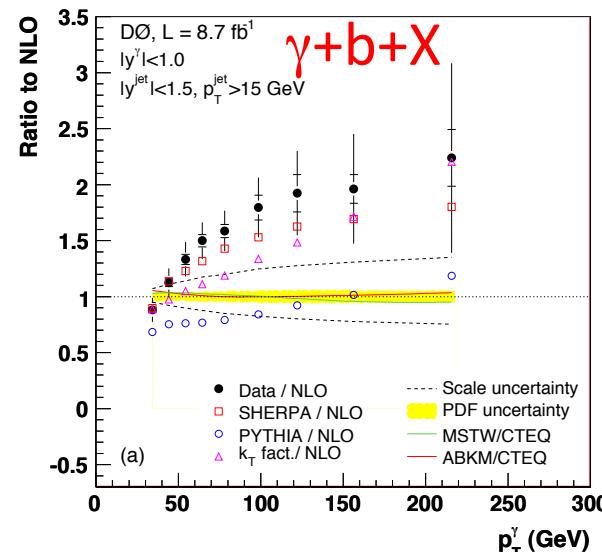
Previous results – D0

PRL 102, 192002 (2009) - 1 fb⁻¹

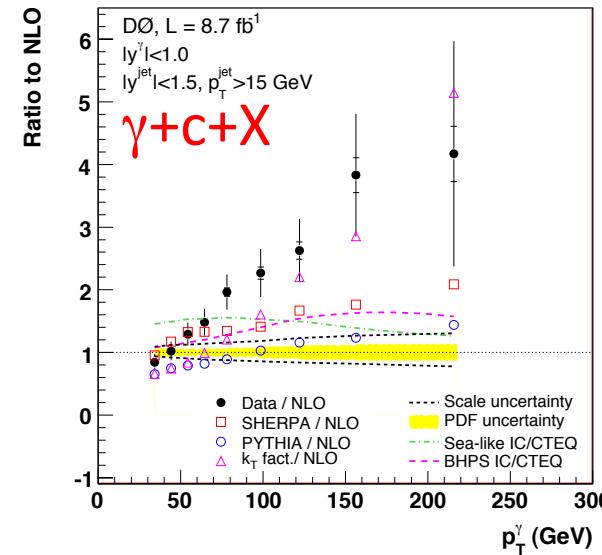


- Good agreement for $\gamma + b + X$
- Discrepancy for $\gamma + c + X$

Phys.Lett. B 714, 32 (2012) – 8.7 fb⁻¹



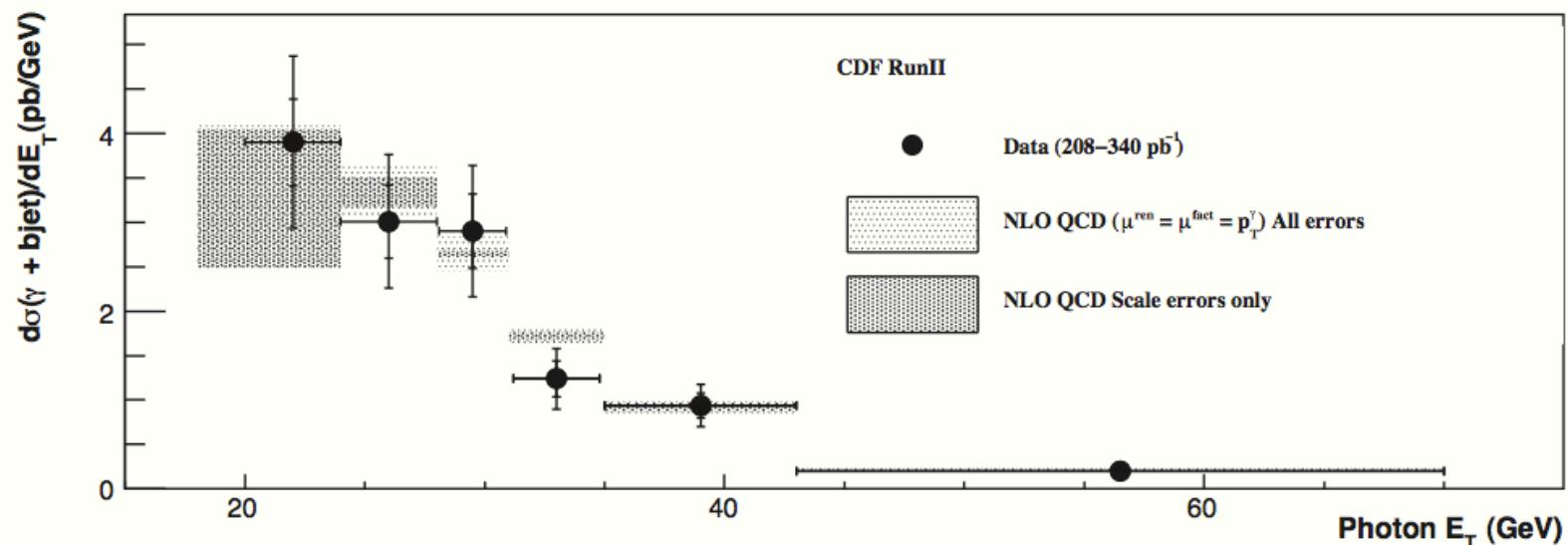
Phys. Lett. B 719, 354 (2013) – 8.7 fb⁻¹



Discrepancies in both channels.

Previous results – CDF

CDF: PRD 81, 052006 (2010) - 340 pb⁻¹



- Measure low p_T cross section using a special trigger
- $\gamma+b+X$ agrees with NLO up to 70 GeV

Analysis overview

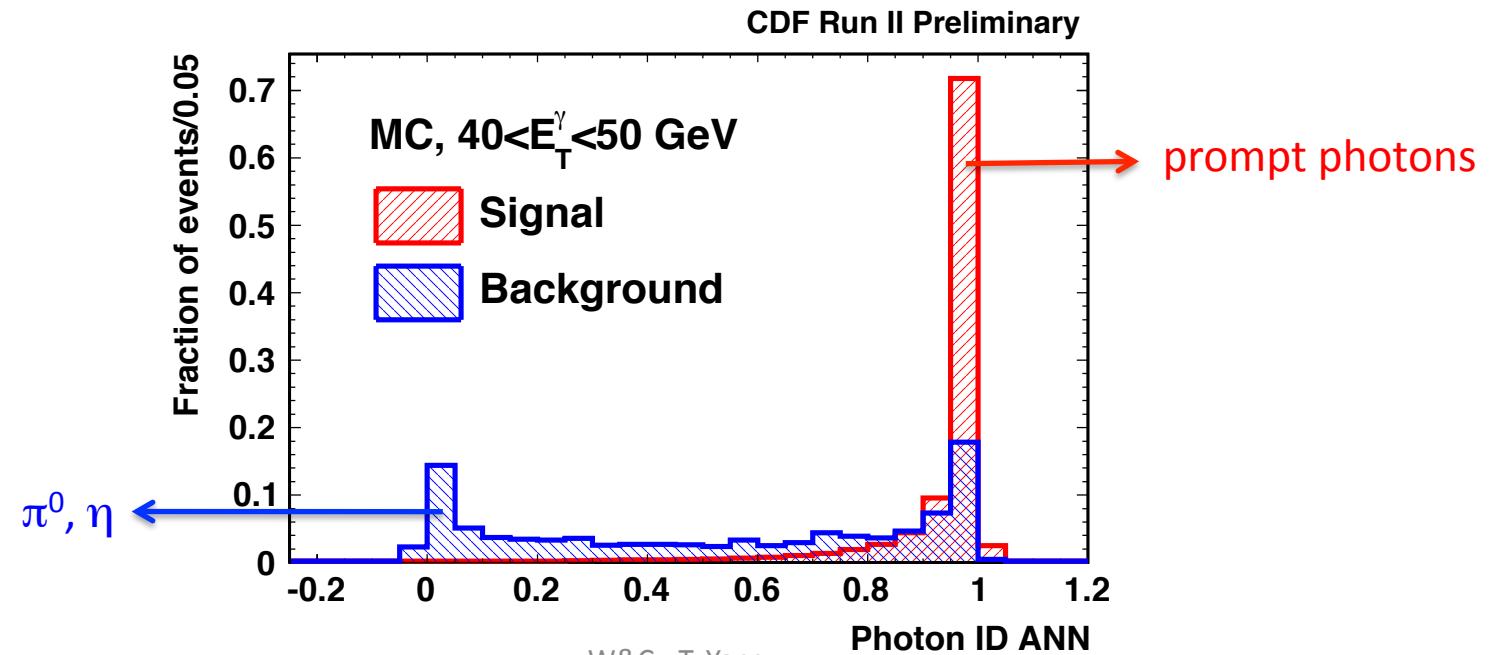
- Measure $\gamma+b/c/X$ cross section using **9.1 fb⁻¹** inclusive photon data collected with CDF II detector
- Use **ANN** (artificial neural network) to select photon candidates
 - Fit ANN distribution to signal/background templates to get photon fraction
- Use **SecVtx** b-tag to select heavy-flavor jets
 - Fit secondary vertex invariant mass to get light/c/b quark fractions
- Use **Sherpa** MC to get efficiency/unfolding factor
 - Photon ID efficiency, b-tagging efficiency, detector acceptance and smearing effects
- Cross section
 - $$\frac{d\sigma}{dE_T^\gamma} = \frac{N \cdot f_\gamma \cdot f_{b/c}}{\varepsilon \cdot A \cdot L \cdot \Delta E_T^\gamma}$$

Event selection

- Use inclusive photon trigger to select photon events
 - Trigger efficiency is approximately **100%** for $\gamma E_T > 30 \text{ GeV}$
- Interaction vertex in the fiducial region
- Photon candidate must pass a neural-net based photon ID
 - **ANN>0.75**
 - $|\eta| < 1.05$, $30 < E_T < 300 \text{ GeV}$, divided into 8 E_T bins
- Jets are reconstructed with **JetClu** cone size 0.4 and must be positively tagged.
 - $|\eta| < 1.5$, $E_T > 20 \text{ GeV}$
- $\Delta R(\gamma, \text{jet}) > 0.4$

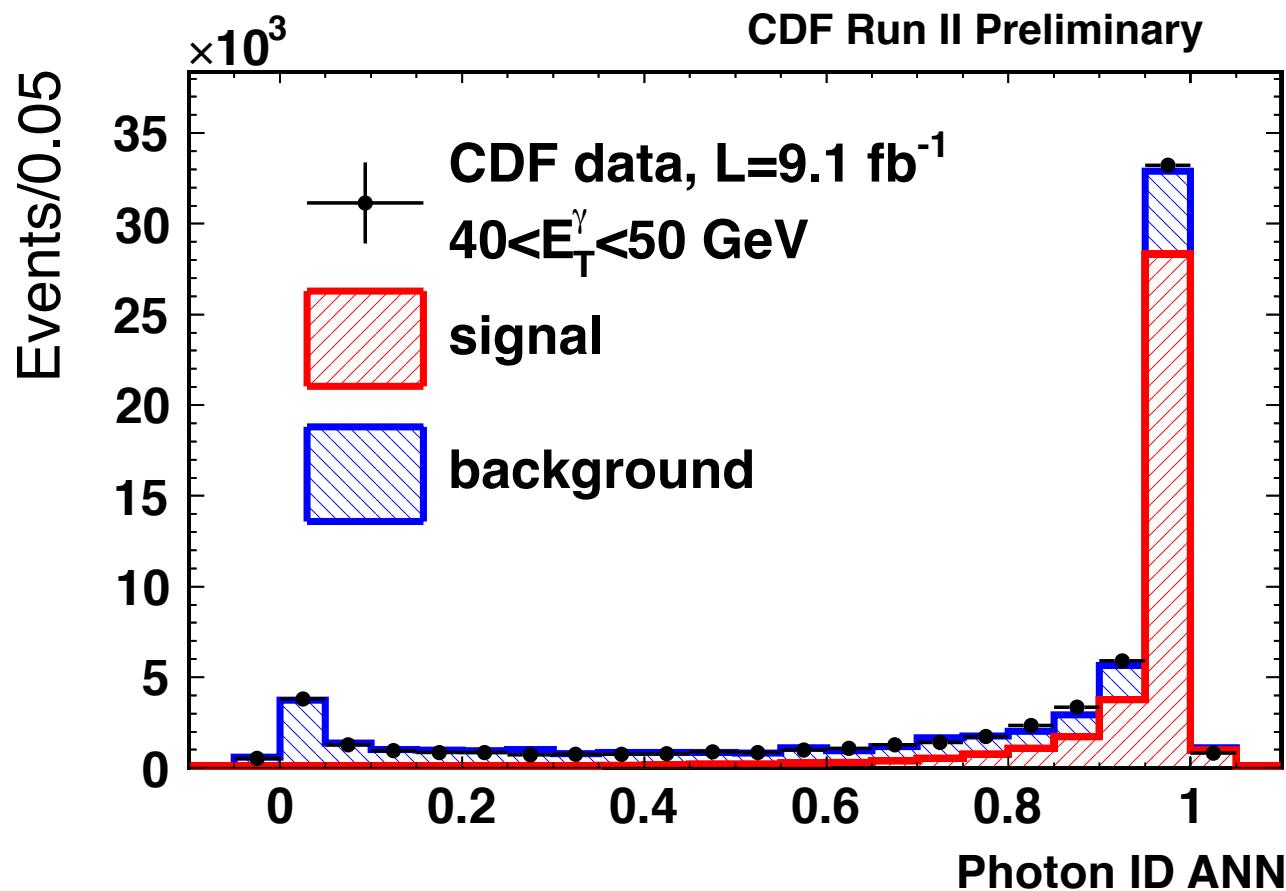
ANN photon ID

- Trained with TMVA (Toolkit for Multivariate Data Analysis)
- 7 input variables to take into account difference between γ and π^0/η : isolation (2), lateral shower shape (3), Had/Em, CES/CEM
- ANN ID improves signal efficiency by 9% at the same background rejection compared with the standard cut-based ID.
- Use MC with full detector simulation to get templates
 - Signal – prompt photons
 - Background – jets with prompt photons removed

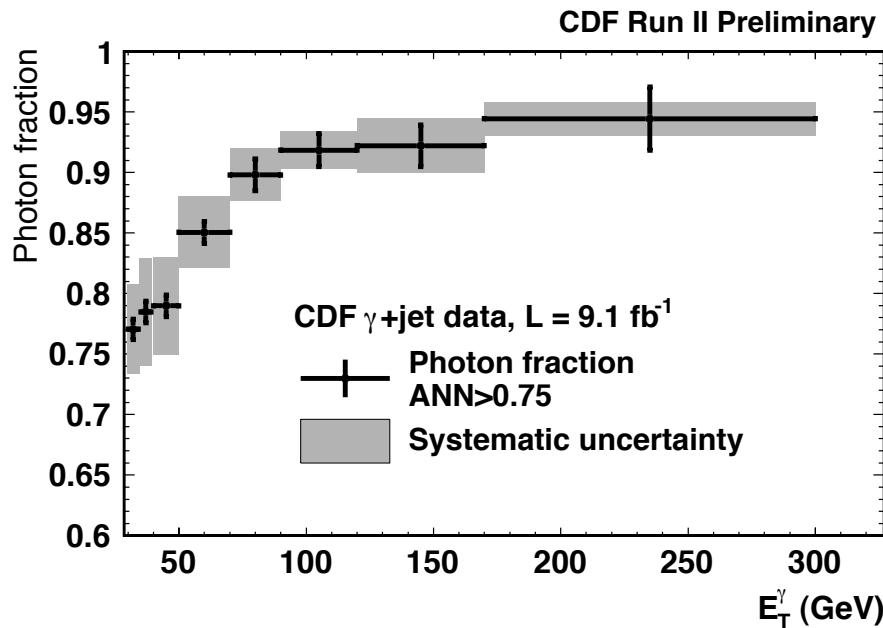


True photon fraction

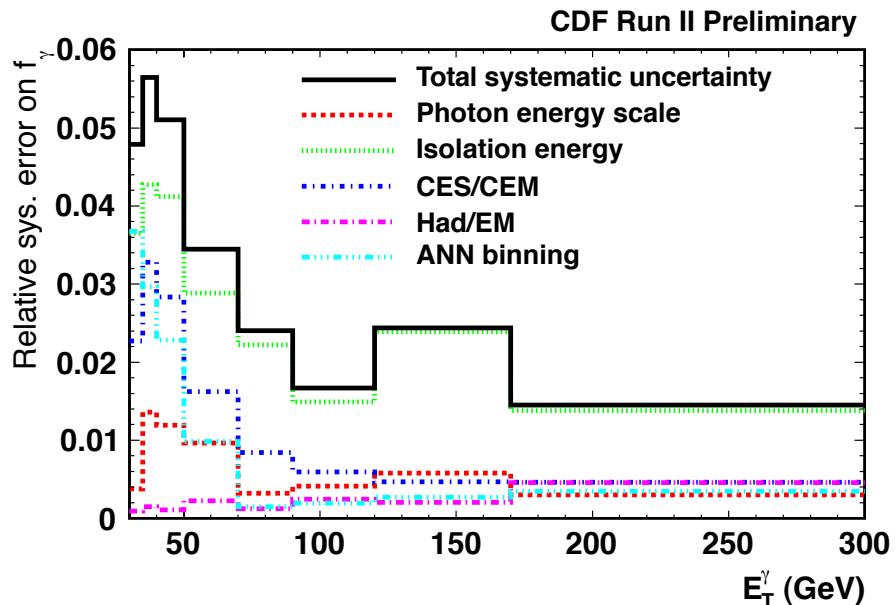
- Fit data ANN distribution using signal and background templates to get true photon fraction



True photon fraction (continued)

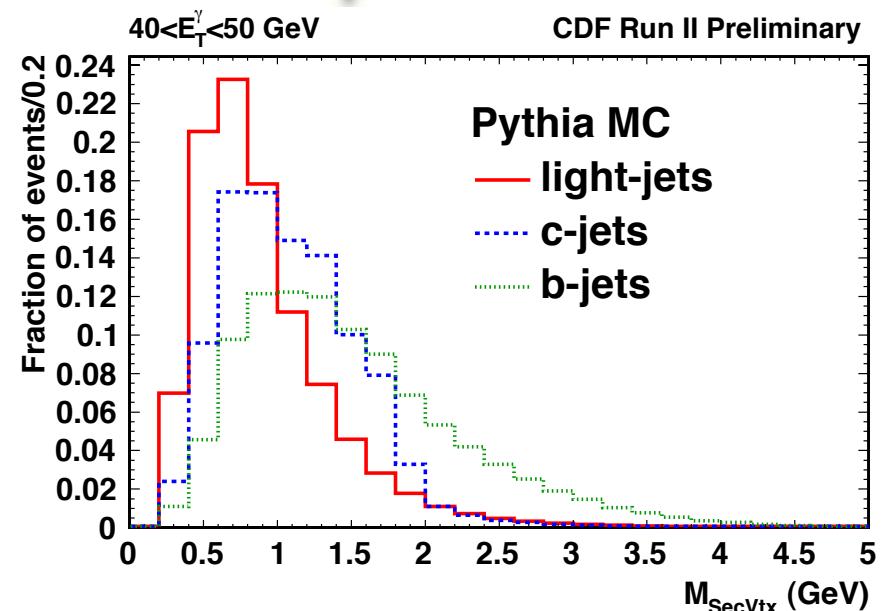
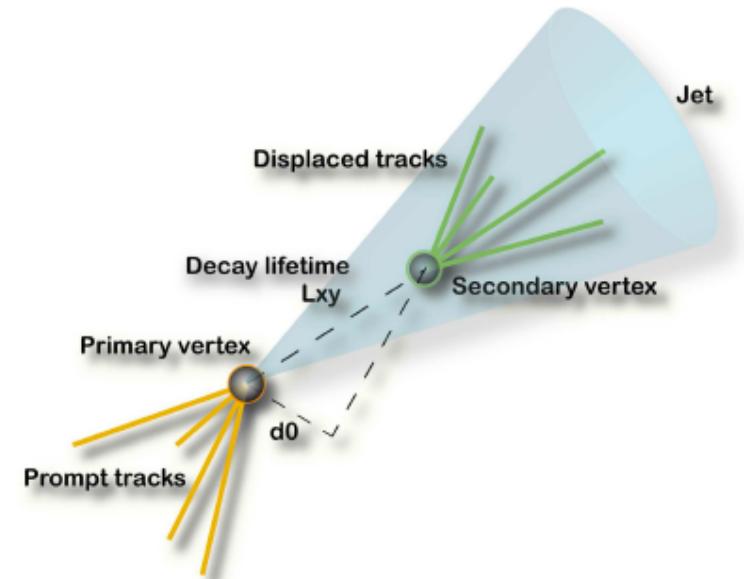


- Systematics
 - Photon energy scale
 - Vary inputs to photon ID ANN according to their uncertainties
 - Vary Photon ID ANN template binning to test sensitivity to shapes
 - 6% at low E_T , 2% at high E_T .

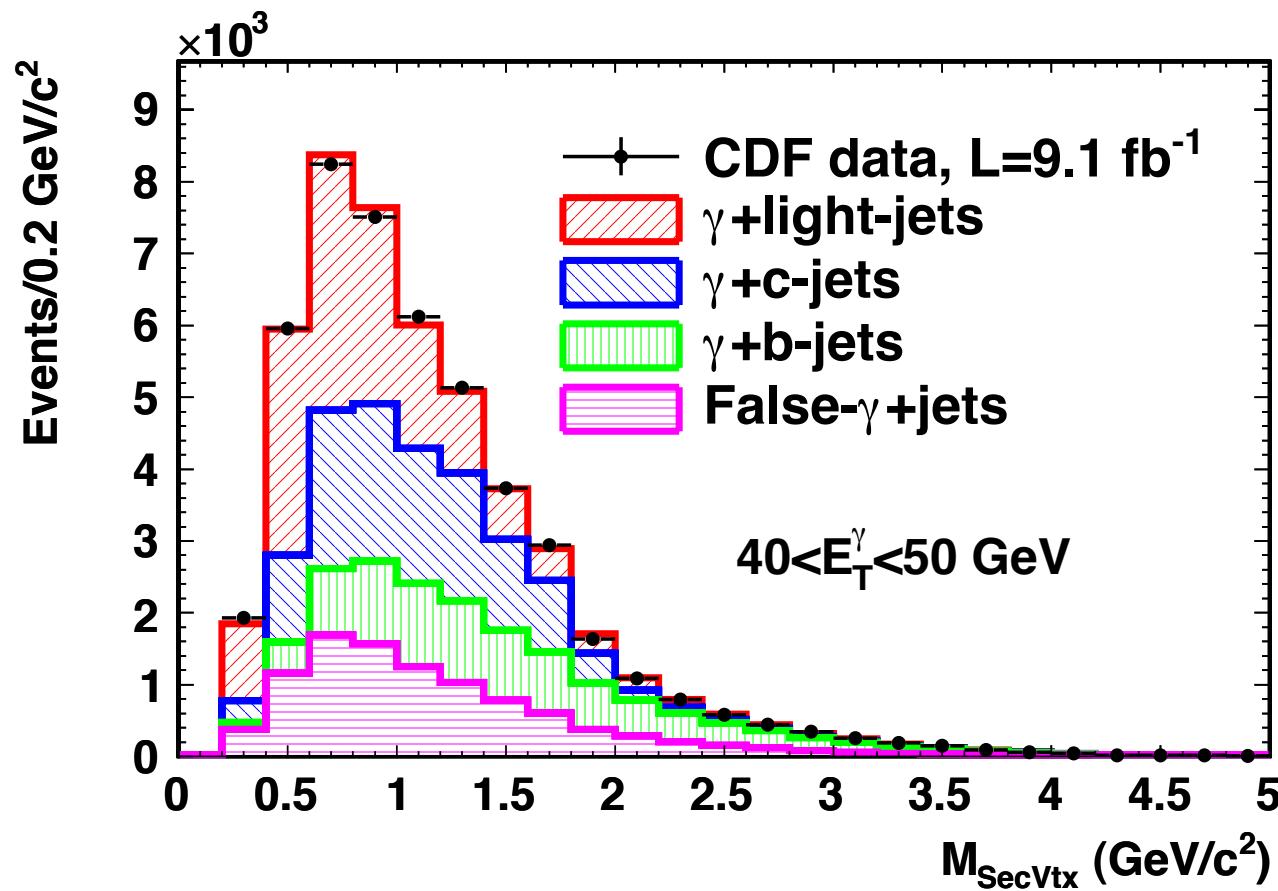


Standard b-jet identification

- B-hadrons are long-lived – search for displaced vertices
- Fit displaced tracks and cut on L_{xy} significance ($\sigma \sim 200 \mu\text{m}$)
- Charm hadrons have similar tag behavior but lower efficiency
- Use “tag mass” to deduce the flavor composition of a sample of tagged jets
 - Mass of the tracks forming the secondary vertex
 - B-hadrons are heavy: will have higher m_{tag} spectrum than charm or light jet fakes

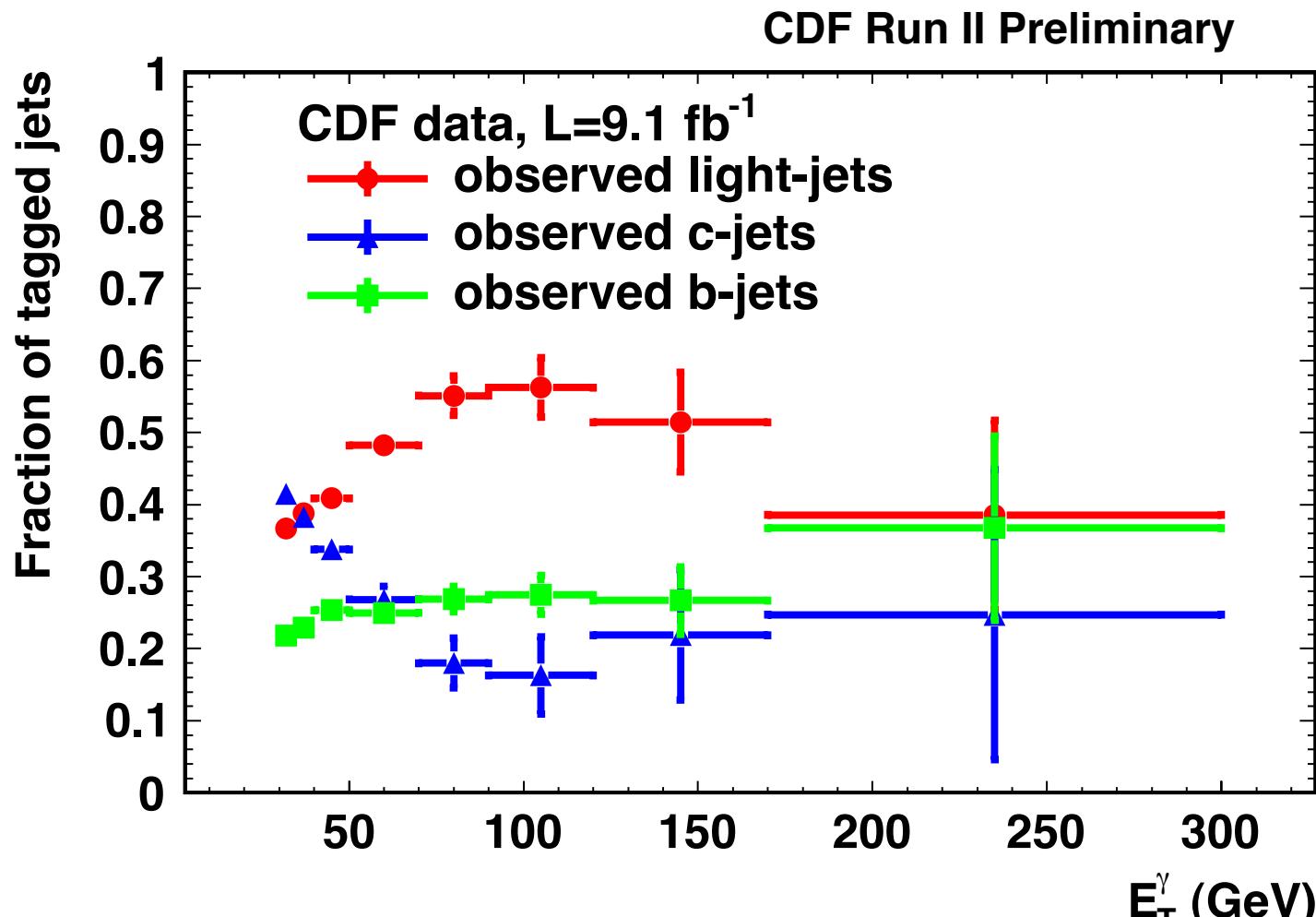


Light/c/b-jet fractions



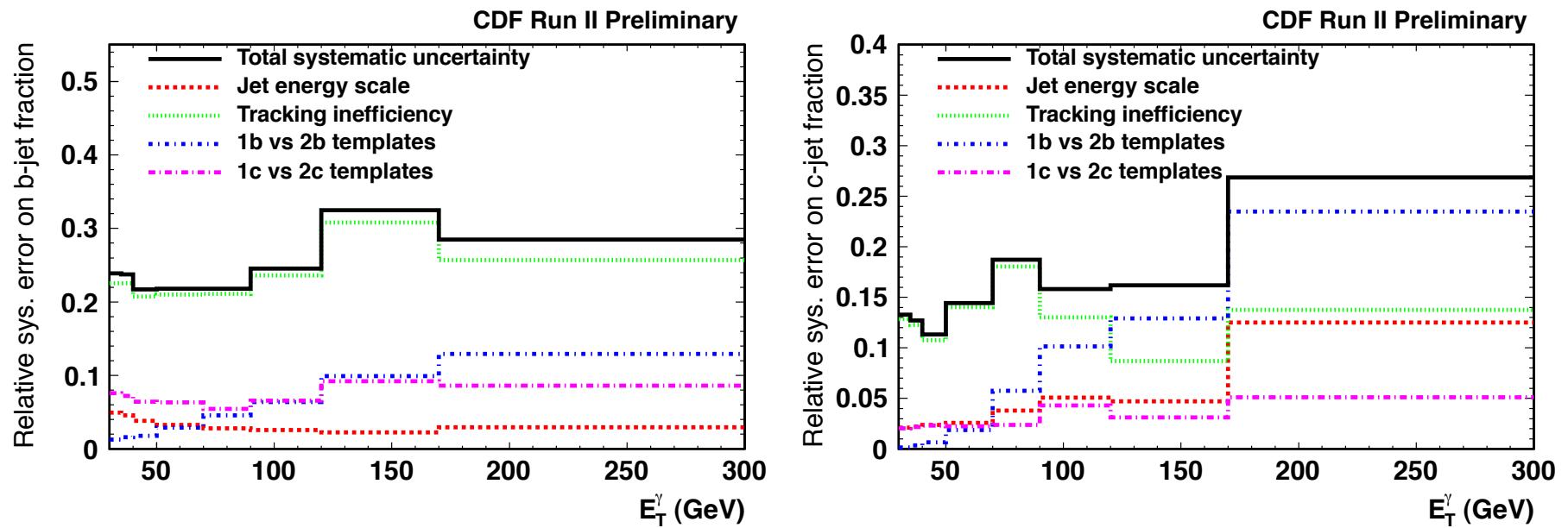
- Fit data secondary vertex mass using MC templates
- Shape of secondary vertex mass for event with fake photon is taken from di-jet data

Light/c/b-jet fractions (continued)



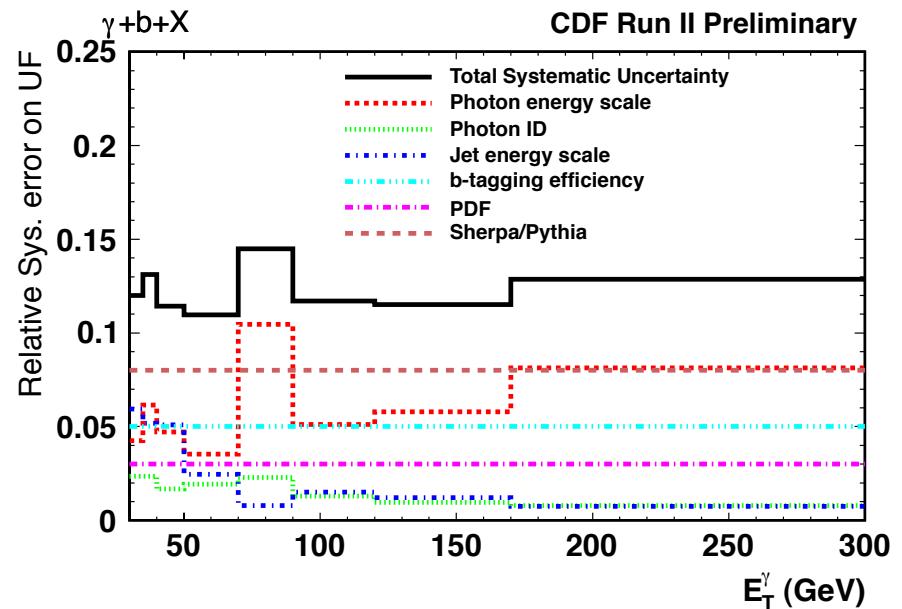
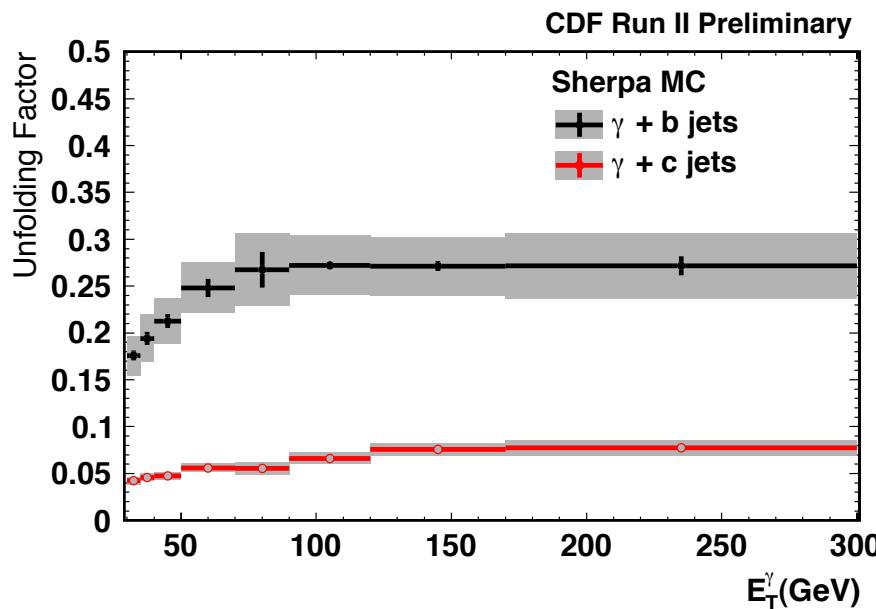
Results from fitter.

Systematics on b/c-jet fractions



- Jet energy scale: affects acceptance
- Uncertainty in tracking efficiency: scale secondary vertex mass templates by $\pm 3\%$
 - Dominant systematic effect
- Difference between single-quark and di-quark jets
- Total systematic error is $\sim 20\%$

Efficiency×Acceptance



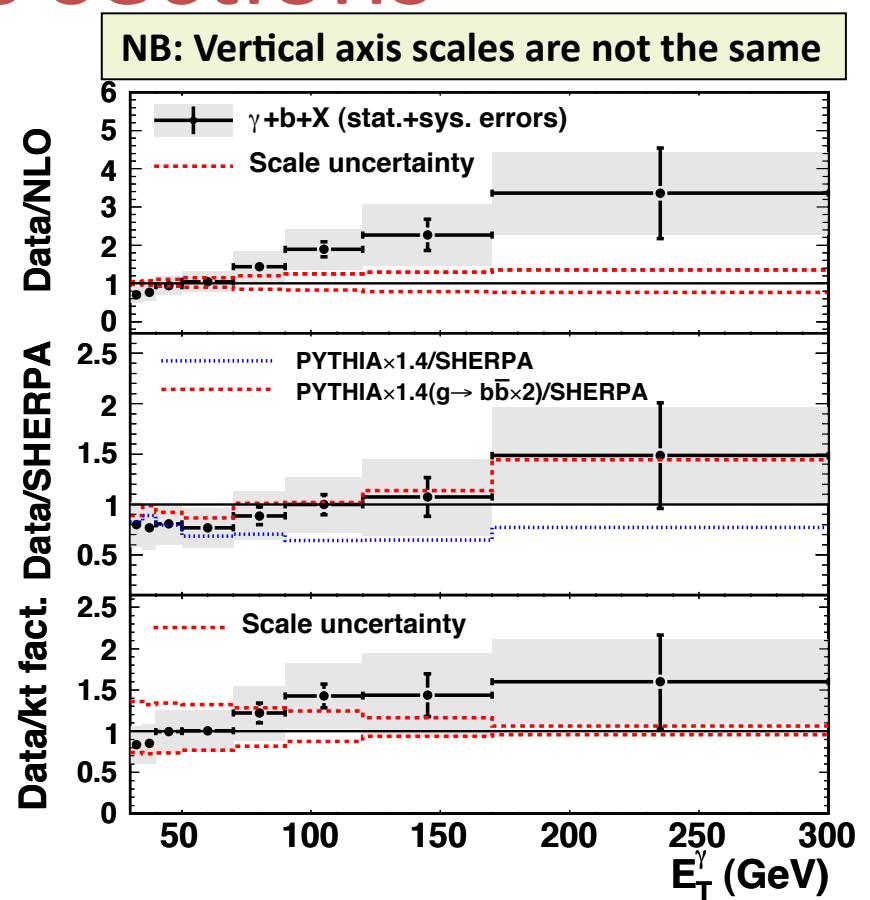
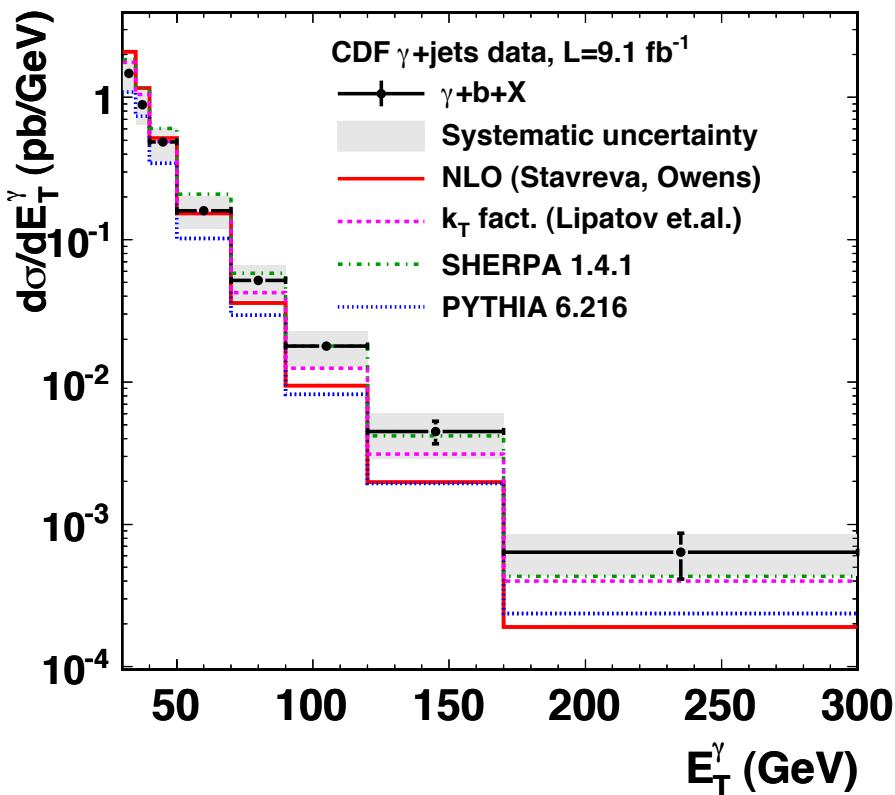
- Use **Sherpa** MC to unfold photon ID efficiency, b-tagging efficiency, detector acceptance and smearing effects.
- Systematic effects evaluated
 - photon energy scale and ID
 - jet energy scale
 - b-tagging efficiency
 - Generator
 - PDF

4 theoretical predictions

- **NLO** – direct-photon subprocesses and fragmentation subprocesses at $\mathcal{O}(\alpha\alpha_s^2)$, CTEQ6.6M PDFs [T.P. Stavreva and J.F. Owens, PRD **79**, 054017 (2009)].
- **k_T -factorization** – off-shell amplitudes integrated over k_T -dependent parton distributions, MSTW2008 PDFs [A.V. Lipatov *et al.*, JHEP **05**, 104 (2012)].
- **Sherpa 1.4.1** – tree-level matrix element (ME) diagrams with one photon and up to three jets, merged with parton shower, CT10 PDFs [T. Gleisberg *et al.*, JHEP **02**, 007 (2009)].
- **Pythia 6.216** – ME subprocesses: $gQ \rightarrow \gamma Q$, $\underline{q}\bar{q} \rightarrow \gamma g$ followed by gluon splitting: $g \rightarrow Q\bar{Q}$, CTEQ5L PDFs [T. Sjöstrand *et al.*, JHEP **05**, 026 (2006)].

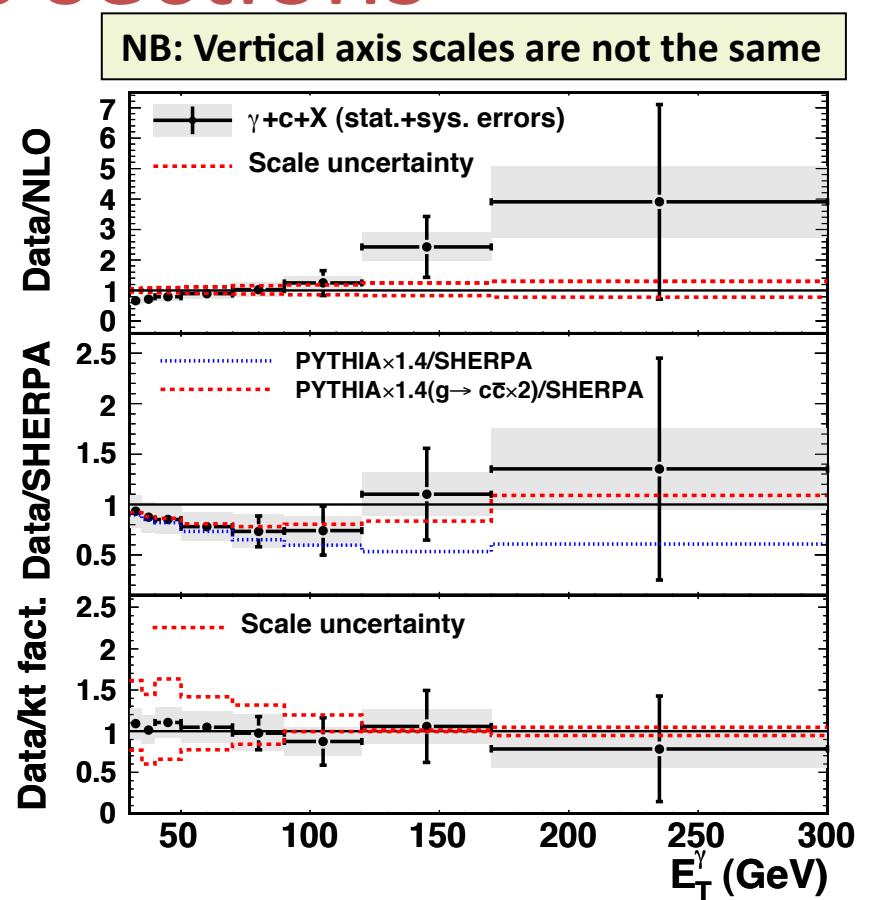
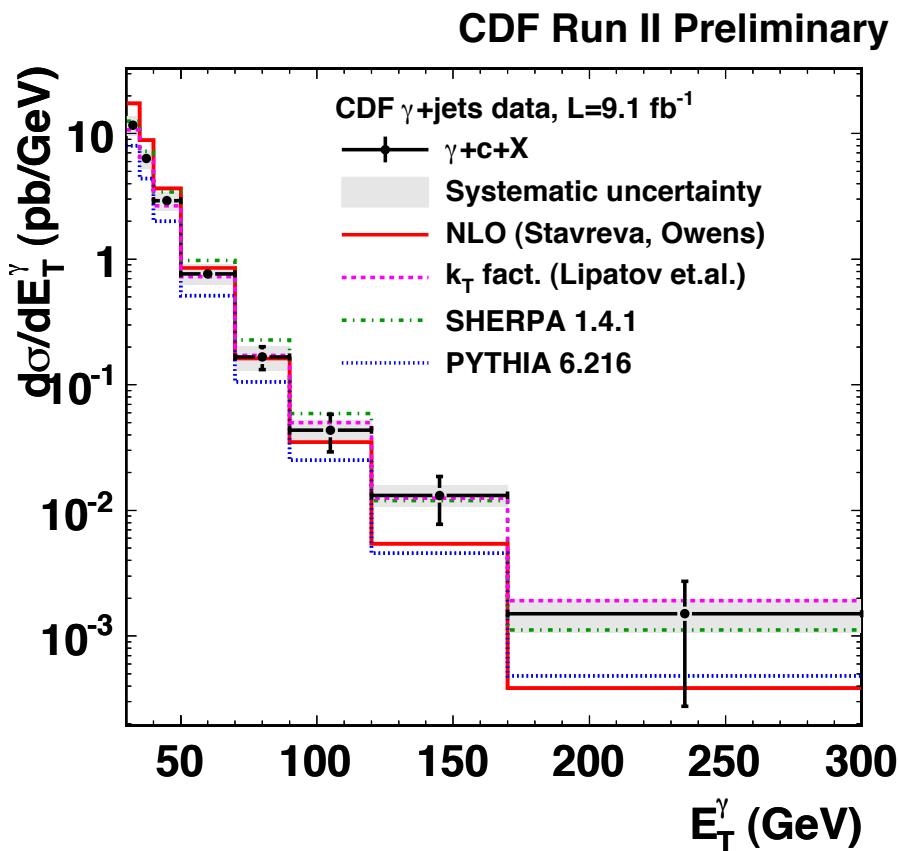
$\gamma+b+X$ cross sections

CDF Run II Preliminary



- NLO fails to describe data at large photon E_T – perhaps gluon splitting is treated at LO.
- k_T -factorization and Sherpa agree with data reasonably well.
- Pythia with doubled gluon splitting rate to heavy flavor describes the shape.

$\gamma+c+X$ cross sections



- NLO fails to describe data at large photon E_T – perhaps gluon splitting is treated at LO.
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Summary of photon+b/c cross sections

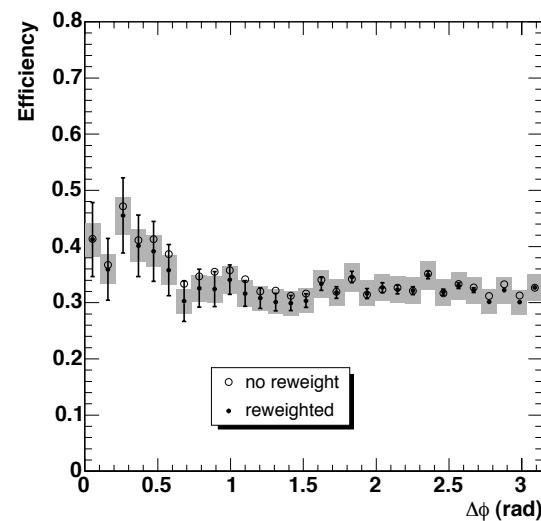
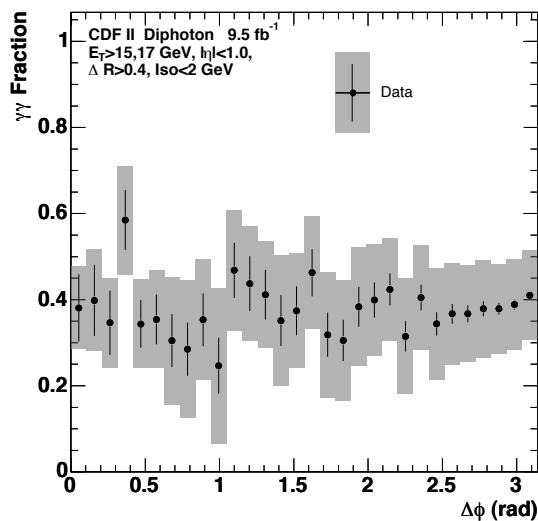
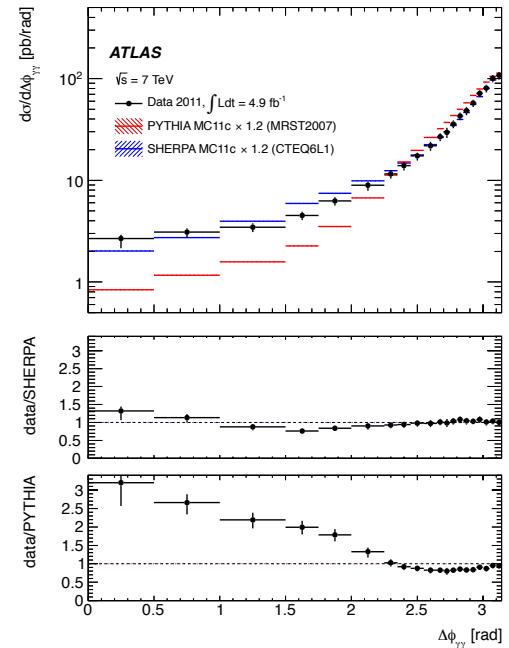
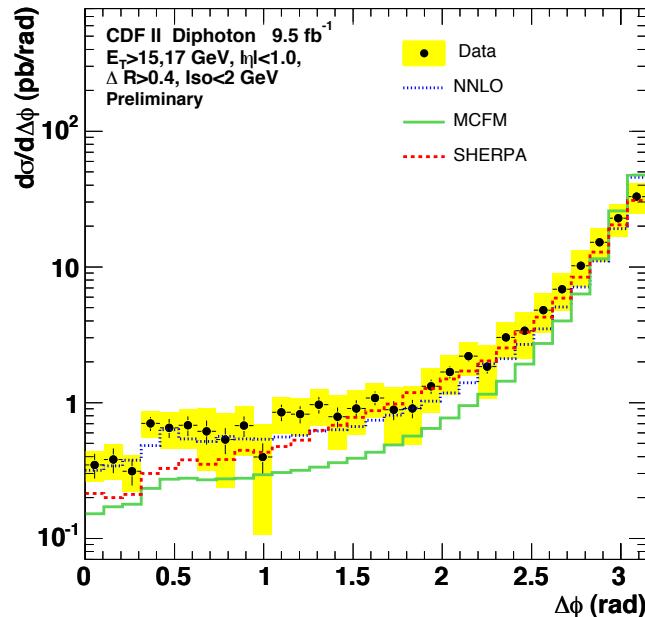
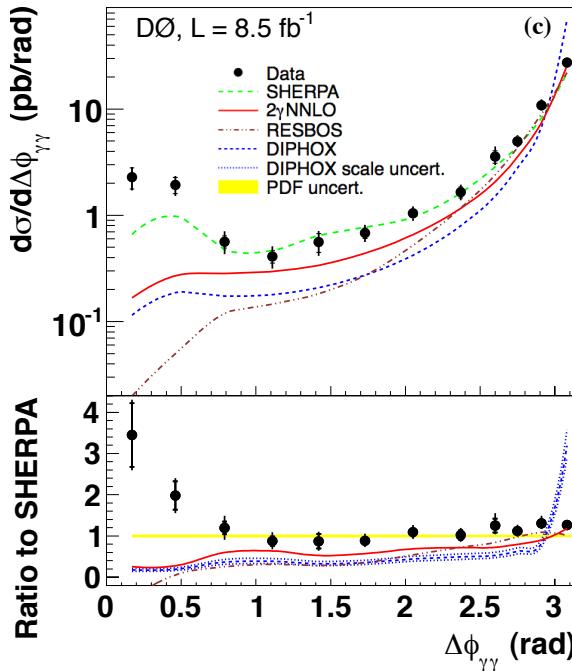
- High precision $\gamma+b/c$ cross sections are measured using the full CDF Run II dataset.
- The data are compared with parton shower, fixed-order and k_T -factorization calculations.
- NLO does not reproduce data most likely because of its limitation in modeling gluon splitting rates.
- k_T -factorization and Sherpa agree with data reasonably well.
- Pythia with doubled gluon splitting rates to heavy flavor describes the data shape.

Conclusions

- The CDF experiment has produced a wealth of QCD physics results and analysis techniques, which is a legacy for the current and future high energy experiments.
- We have achieved an unprecedented level of precision for many photon-related observables.
- Those results provide invaluable information to the HEP community, *e.g.* the diphoton results will help the precision measurements of H boson in the $\gamma\gamma$ channel.
- ... and we are not done yet!!

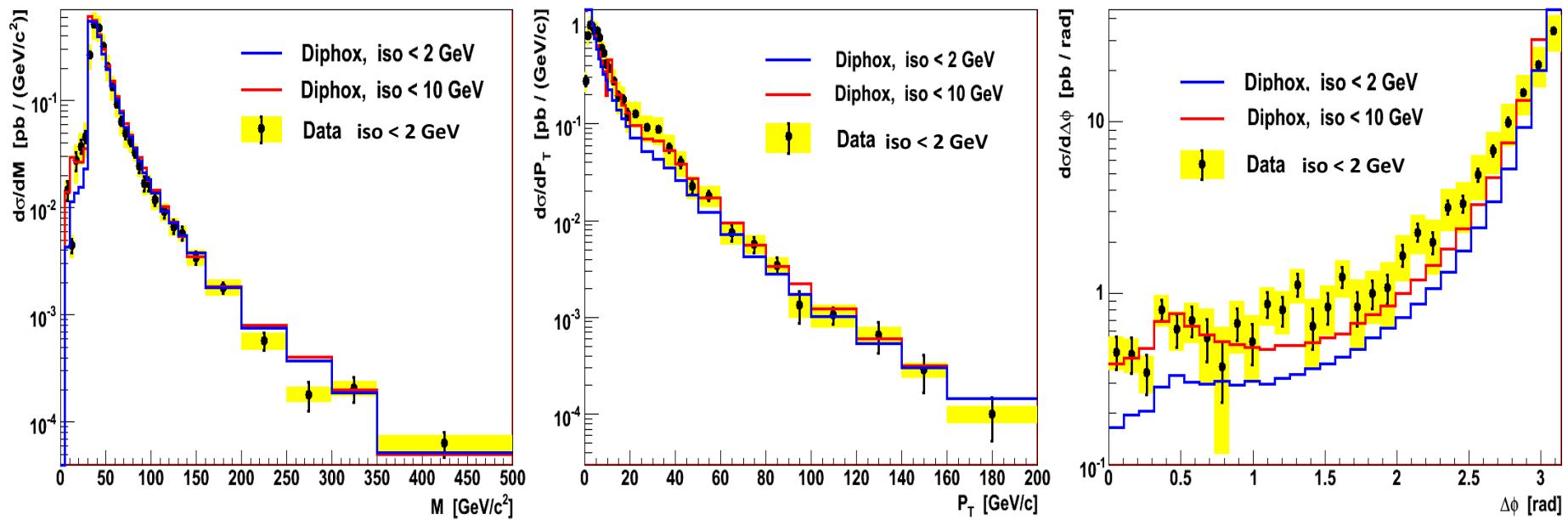
	Integrated cross section (pb)
Data (CDF)	$12.3 \pm 0.2_{\text{stat}} \pm 3.5_{\text{syst}}$
RESBOS	11.3 ± 2.4
DIPHOX	10.6 ± 0.6
MCFM	11.5 ± 0.3
SHERPA	12.4 ± 4.4
PYTHIA gg+gj	9.2
NNLO	$11.8 + 1.7 - 0.6$

Comparison with D0



$$\frac{d\sigma}{dX} = \frac{N_{\gamma\gamma}}{\varepsilon \cdot A \cdot L \cdot \Delta}$$

A closer look at fragmentation: DIPHOX isolation study



Fragmentation strength is missing from the DIPHOX calculation possibly because of the approximate application of the isolation requirement at the parton level

A closer look at fragmentation: DIPHOX isolation study

